UNIVERSIDADE ESTADUAL PAULISTA – UNESP

CENTRO DE AQUICULTURA DA UNESP

CONTABILIDADE AMBIENTAL DE SISTEMAS SEMI-INTENSIVOS DE AQUICULTURA: ESTUDO DE CASO DA LAMBARICULTURA

Tamara Fonseca de Almeida

Jaboticabal, São Paulo

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Orientador: Prof. Dr. Wagner C. Valenti

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AUTORA: TAMARA FONSECA DE ALMEIDA
ORIENTADOR: WAGNER COTRONI VALENTI

Aprovada como parte das exigências para obtenção do Título de Doutora em AQUICULTURA, pela Comissão Examinadora:

Prof. Dr. WAGNER COTRONI VALENTI (Participaçao Virtual)
Setor de Carcinicultura / Centro de Aquicultura da UNESP, CAUNESP, Jaboticabal-SP

Prof. Dr. Danilo Cintra Proença (Participação Virtual)
Faculdades São Luiz Jaboticabal, SP

Dr. RODRIGO ROUBACH (Participação Virtual)
Senior Aquaculture Officer / FAO-ONU, Roma-Itália

Prof. Dr. FENI DALANO ROOSEVELT AGOSTINHO (Participação Virtual)
Engenharia de Produção / Universidade Paulista, UNIP, Mirandópolis-SP

Prof. Dr. BIAGIO FERNANDO GIANNETTI (Participação Virtual)
Engenharia de Produção / Universidade Paulista - UNIP, Mirandópolis-SP

Jaboticabal, 01 de março de 2021

Centro de Aqüicultura da Unesp
Coordenação do Programa de Pós-Graduação
Via de Acesso Prof. Paulo Donato Castellane, s/n CEP 14884-900 Jaboticabal SP Brasil
Tel 55 16 32032110 ramal 214 fax 55 16 32032268
pgaqui@caunesp.unesp.br www.caunesp.unesp.br

DEDICATÓRIA

Aos pequenos produtores rurais do Brasil.

“Fomos, durante muito tempo, embalados com a história de que somos a humanidade. Enquanto isso, fomos nos alienando desse organismo de que somos parte, a Terra, e passamos a pensar que ele é uma coisa e nós, outra: a Terra e a humanidade. Eu não percebo onde tem alguma coisa que não seja natureza. Tudo é natureza [...]. Enquanto isso, a humanidade vai sendo descolada de uma maneira tão absoluta desse organismo que é a Terra. Os únicos núcleos que ainda consideram que precisam ficar agarrados nessa Terra são aqueles que ficaram meio esquecidos pelas bordas do planeta, nas margens dos rios, nas beiras dos oceanos, na África, na Ásia ou na América Latina. ”

(Ailton Krenak, Ideias para adiar o fim do mundo)

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Agradeço ao meu companheiro Fabio, pelos anos dedicação e respeito, e por ser o meu porto seguro e maior incentivador em momentos de dificuldade. Agradeço às grandes amigas, Pie, Camila, Carol, Pri, Vuvu, Rebeka, Jô, Tavani, Stéfany, Duda e Fernanda, pelo incentivo, apoio e acolhimento de sempre: “quem tem um amigo tem tudo”. À Bruna, por me ajudar a enxergar o caminho com mais clareza. À minha família, em especial a minha irmã Vanessa, minha mãe Eliana e meu pai Antonio, sem os quais esse sonho sequer existiria.

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SUMÁRIO

RESUMO

A aquicultura pode ser uma ferramenta para conciliar o desenvolvimento socioeconômico à conservação dos recursos naturais, contribuindo para o desenvolvimento sustentável de comunidades rurais. A atividade vem crescendo de forma acelerada no Brasil e é realizada majoritariamente por pequenos produtores rurais, com o uso de sistemas semi-intensivos de água doce. Os lambaris são um grupo de peixes nativos com alto potencial para a aquicultura sustentável. Dessa forma, o presente estudo tem como objetivo avaliar a sustentabilidade dos sistemas de produção de lambari-do-rabo-amarelo por três diferentes abordagens: síntese em emergia, funções ecossistêmicas e avaliação multicritério dos cinco setores. Os resultados indicam que os níveis de controle do produtor (baixo, moderado e alto) sobre as práticas de manejo afetam a eficiência na utilização de recursos naturais. Além disso, os viveiros de aquicultura são ecossistemas antrópicos que podem ser manejados para a maximização de externalidades positivas e minimização de externalidades negativas, aumentando a resiliência dos sistemas produtivos por meio da restauração dos recursos naturais, dos quais ele depende. Finalmente, os sistemas de baixo controle são socialmente mais sustentáveis e contribuem mais para o desenvolvimento local, enquanto os sistemas de moderado e alto controle são economicamente mais lucrativos e utilizam os recursos naturais de forma mais eficiente.

PALAVRAS CHAVE: sustentabilidade; economia ambiental; desenvolvimento rural; peixes tropicais; aquicultura de água doce; pequenos produtores; uso de recursos naturais.

ABSTRACT

Aquaculture can be a tool to reconcile socioeconomic development with the conservation of natural resources, contributing to the sustainable development of rural communities. The activity has been growing fast in Brazil, and is performed mainly by small rural producers, in semi-intensive freshwater systems. Lambari is a group of native fish with high prospects for sustainable aquaculture. Therefore, this study aims to access the sustainability of the lambari aquaculture production in Brazil by three approaches: emergy synthesis, ecosystem functions, and multi-criteria assessment of the five-sectors sustainability model. The results indicate that the levels of control (low, moderate and high) over the management practices adopted by farmers affect the efficiency of natural resources consumption. In addition, aquaculture ponds are man-made ecosystems that can be managed to maximize positive externalities and minimize negative externalities, increasing the resilience of the productive systems by restoring the natural resources in which they depend. Finally, the low-control systems are more sustainable socially, and contribute more to local development, while moderate and high-control systems are higher economically feasible and use natural resources more efficiently.

KEYWORDS: sustainability; freshwater aquaculture; smallholder farms; natural resources consumption.

INTRODUÇÃO GERAL

Conciliar o desenvolvimento socioeconômico à conservação dos recursos naturais é um dos maiores desafios globais para o desenvolvimento de comunidades rurais (Goswami et al., 2017; Jung et al., 2017). A aquicultura pode ser uma ferramenta para a solução desse problema. Ela tem o potencial de ser mais sustentável quando comparada às monoculturas agrícolas e à produção de animais terrestres (Costa-Pierce and Page, 2010). Além disso, a aquicultura pode contribuir para a geração de renda e empregos diretos, indiretos e auto-empregos, e produzir alimentos de alto valor nutricional (Béné et al., 2016).

Os principais desafios atuais para o progresso da aquicultura de água doce em países em desenvolvimento, como o Brasil, estão relacionados à regulamentação governamental, a falta de uma cadeia produtiva bem estruturada, aos impactos e poluição ambiental, fuga de espécies exóticas e híbridas interespecíficas, bem-estar e saúde animal, nutrição adequada e suporte técnico (Boyd et al., 2020; Brugère et al., 2019; Henares et al., 2019). A comunidade científica tem desenvolvido diversas tecnologias para enfrentar alguns desses desafios, tais como: tecnologia para tratamento de efluentes, pacotes tecnológicos para o cultivo de espécies nativas, medicamentos e probióticos, melhoramento genético, diminuição da taxa de conversão alimentar, substituição da farinha de peixe na ração por proteína vegetal e sistemas de recirculação (Antonucci and Costa, 2020; Dawood et al., 2019; Humphries et al., 2019; Lulijwa et al., 2019; Tacon, 2020). Apesar das expressivas melhoras alcançadas, a maioria destas soluções são caras e, por vezes, inatingíveis por pequenos produtores rurais. Além disso, a tecnologia atual pode se revelar ineficaz na mitigação das ameaças complexas causadas pela crise da COVID19 e pelas mudanças climáticas em um futuro próximo. Reconhecendo que o modelo de “business as usual” não tem contemplado essas questões, tecnologias inovadoras na aquicultura, que possam se ajustar a esses desafios, serão vitais para sua sustentabilidade a longo prazo (United Nations, 2020).

A aquicultura é o setor de produção de alimentos que cresceu mais rápido nas últimas décadas, e tem previsão de crescer 37% até 2030 (Garlock et al., 2020). A produção aquícola mundial atingiu 82.1 milhões de toneladas de pescados e 32.4

milhões de toneladas de plantas aquáticas em 2018, e já ultrapassou a pesca em 35 países. O Brasil ocupa a 8ª posição no ranking mundial de maiores produtores de peixes pela aquicultura (FAO, 2020). A produção aquícola em 2019 foi de aproximadamente 800.000 toneladas, o que representa uma receita bruta de ~US$ 1 bilhão. Atualmente, mais de 200 mil fazendas de piscicultura de água doce estão em atividade no Brasil (Valenti et al., 2021). As espécies de água doce são as mais produzidas, sendo que a tilápia (*Oreochromis niloticus*) e o tambaqui (*Colossoma macropomum*) são predominantes (IBGE, 2020). No entanto, outras espécies nativas, como o lambari (*Astyanax lacustris*), possuem alta relevância socioeconômica regional. Além disso, a maior parte da produção aquícola brasileira vem de pequenas propriedades rurais (<2 ha), onde o cultivo é realizado em viveiros escavados de água doce (Valenti et al., 2021).

Entre as espécies de peixes nativos com grande potencial para a aquicultura, destaca-se os lambaris (Fonseca et al., 2017). O cultivo surgiu como uma fonte de renda alternativa para pequenos produtores rurais no sudeste brasileiro. A produção cresceu nos últimos anos baseada no mercado de iscas vivas para pesca recreativa. No entanto, além do uso como iscas, o lambari também é consumido como aperitivo em bares e restaurantes. Algumas espécies apresentam grande potencial para o mercado de peixes ornamentais. Ainda, o uso como um substituto mais sustentável das sardinhas utilizadas na pesca industrial de atum tem sido investigado. A maioria dos lambaricultores é formada por pequenos produtores familiares, que adotam sistemas de produção semi-intensivos em viveiros de fundo natural e a principal espécie cultivada é o lambari-do-rabo-amarelo (*Astyanax lacustris*) (Fonseca et al., 2017). Porém, uma recente expansão no mercado tem atraído investidores com mais capital, que operam em fazendas maiores (> 20 ha) e demandam infraestrutura mais complexa.

Fonseca et al. (2017) revisaram as informações disponíveis sobre a produção de lambaris e identificaram que os sistemas de cultivo e estratégias de produção variam entre os produtores. Cada produtor estabeleceu a sua estratégia empiricamente ou baseado em protocolos para outras espécies (Silva et al., 2011). Práticas de manejo menos eficientes são frequentemente adotadas e as informações científicas são insuficientes para gerar tecnologias adequadas às necessidades dos produtores (Fonseca et al., 2017). Além disso, pelo fato de não existir dieta comercial específica para o lambari, os produtores escolhem a ração com base no tamanho do pélete que o animal é capaz de ingerir (Silva et al., 2011); essa situação persiste ainda em 2020. Comumente são usadas dietas desenvolvidas para juvenis de outras espécies, com alta concentração de proteína bruta e de alto custo financeiro. Esses fatores implicam em baixa produtividade e uso inadequado dos recursos naturais (Fonseca et al., 2017).

Como espécie nativa e de baixo nível trófico, o lambari tem potencial para ser produzido de forma sustentável, promovendo o desenvolvimento socioeconômico e conservando os recursos naturais. A diversidade de mercados permite a atuação de produtores de diferentes tamanhos e níveis de tecnificação. Além disso, o cultivo de lambaris pode ser implantado em pequenas propriedades como atividade complementar, aumentando a renda familiar. Porém, para que essas potencialidades sejam atingidas, é essencial conhecer os sistemas de produção usados e a conjuntura nas quais eles se inserem para identificar seus pontos fracos e sugerir alternativas. Assim, medir a sustentabilidade dos sistemas permite identificar os principais gargalos, bem como conhecer as forças condicionantes da produção sustentável. Com base nessas informações, pode-se tornar a produção mais eficiente e adequada à realidade de cada produtor, bem como aumentar a sustentabilidade ambiental, econômica e social.

No capítulo 1, a sustentabilidade dos sistemas de produção de lambari foi avaliada sob a ótica da Síntese em Emergia. Emergia, com "m", compreende toda a energia utilizada direta ou indiretamente para a produção de um bem ou serviço (Odum, 1996). Utilizando esse método, foi possível quantificar o investimento da natureza no sistema produtivo sob uma abordagem eco-cêntrica. Ainda, foi possível avaliar a dependência dos sistemas sobre os recursos naturais renováveis e não-renováveis, e compará-los identificando quais estratégias de manejo da produção são mais ou menos eficientes na utilização dos recursos.

No capítulo 2, foram avaliadas as principais funções ecossistêmicas que ocorrem nos viveiros escavados utilizados para a lambaricultura, e de quais formas elas influenciam na prestação de serviços e desserviços ecossistêmicos. As funções ecossistêmicas são os processos ecológicos que controlam os fluxos de energia, matéria orgânica e nutrientes nos ecossistemas naturais (Lee and Brown, 2021). Os viveiros de aquicultura podem ser vistos como ecossistemas antrópicos, manejados para maximizar o serviço de provisão de biomassa: peixes. No entanto, outros serviços como, regulação de microclima, e desserviços como a geração de efluentes, ocorrem simultaneamente. Dessa forma, as estratégias de manejo que maximizam os serviços e minimizam os desserviços foram investigadas.

Finalmente, no capítulo 3, os sistemas de lambaricultura foram avaliados pela ferramenta de análise multicritério de sustentabilidade dos cinco setores (5SEnSU). Ela se baseia na premissa de que os sistemas humanos são considerados termodinamicamente abertos, os quais demandam energia e materiais advindos da natureza, que serão transformados em bens e serviços por meio do trabalho humano (Giannetti et al., 2019). De acordo com modelo conceitual 5SEnSU, o meio ambiente atua como fornecedor de recursos naturais (setor 1) e recebedor de subprodutos e resíduos (setor 2) do setor produtivo (setor 3). Por outro lado, a sociedade atua como fornecedora de mão-de-obra e tecnologia (setor 4), e recebedora dos bens e serviços (setor 5) produzidos pelo setor 3 (Giannetti et al., 2019). Este modelo permite uma visão holística do sistema produtivo, que ocorre por meio da quantificação das trocas físicas que ocorrem entre os setores ambiental, econômico e social, o que confere uma mensuração cientificamente robusta da sustentabilidade dos sistemas produtivos.

CAPÍTULO 1: Environmental accounting of the yellow-tail lambari farming: small changes do make a difference

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Environmental accounting of the yellow-tail lambari aquaculture: small changes do make a difference.

Tamara Fonseca[a1], Wagner C. Valenti[a,b], Biagio F. Giannetti[c], Fernando H. Gonçalves[a], Feni Agostinho[c]

[a] Aquaculture Center, São Paulo State University (UNESP). Road Paulo Donato Castellane, Jaboticabal -SP, zip code 14884-900, Brazil.
[b] Innovation Agency of São Paulo State University (AUIN/UNESP): Reitoria da UNESP, Quirino de Andrade Street 215, zip code: 01049-010 - São Paulo - SP – Brazil.
[c] Post-graduation Program on Production Engineering, Paulista University (UNIP). Luís Góis Street 2211, zip code: 04043-200, São Paulo – SP – Brazil.

Abstract

Freshwater pond aquaculture is the prevailing fish culture system worldwide, especially in developing countries. Climate change outcomes and inadequate environmental practices challenge its sustainability. This study applies emergy synthesis to assess the environmental performance of freshwater pond aquaculture in Brazil, aiming to identify and propose management practices towards sustainability. As a study model, nine semi-intensive lambari farms operating at three levels of management were evaluated: low (LC), moderate (MC) and high (HC) control. Results showed that the main inputs for LC are services (27-46%), feed (7-39%) and water (15-21%), while for the MC farms, the main inputs are feed (35-49%) and services (33-39%), and for HC farms, the main flows are feed (17-48%) and services (26-36%). All farms required more than 60% of their emergy from purchased inputs, resulting in low emergy sustainability index (ESI). By replacing fish meal and fish oil by vegetal protein and oil on feed, using superficial water instead of spring water, increasing juvenile productivity, and controlling pond fertilization improved the emergy performance, leading all systems to higher efficiency and resilience. Therefore, simple changes in culture practices do make a difference.

Keywords: Best management practices; Brazil; Emergy; Fish production.

[1] Corresponding author: MSc. Tamara Fonseca, São Paulo State University (UNESP), Aquaculture Center, Road Paulo Donato Castellane, Jaboticabal, Zip code 14884-900, São Paulo, Brazil, Phone +55 11 984876352. Email address: tamara.fonseca@unesp.br, ta.fonseca@hotmail.com.

1. Introduction

The sustainable development was stated as a fundamental goal in the ecosystem approach for aquaculture (EAA) document published by FAO in 2008 (Soto et al., 2008), and it still remains a major concern (Boyd et al., 2020; FAO, 2020). Discussions on the sustainability of aquaculture have focused on the assessment of different production systems or levels of intensification. Different methods in quantifying sustainability has been used, such as life cycle assessment, sets of sustainability indicators, and emergy (with an 'm') synthesis. Additionally, innovative systems, such as integrated multi-trophic aquaculture (IMTA), aquaponics and bioflocs have been developed to achieve higher productivity and sustainability (Henares et al., 2019; Mungkung et al., 2013; Valenti et al., 2018; Wilfart et al., 2013). The majority of the aquaculture systems are small-scale and inland located, despite that fact, they have received less attention in strategic planning and management within EAA concepts than coastal and marine systems (Brugère et al., 2019). Possibly, the EAA framework lacks of a systemic approach to understand how small-scale aquaculture works, i.e. the ways they are connected with the surrounding social, economic and environmental systems.

The small-scale inland aquaculture should shift to more sustainable production systems in order to achieve the goals established by EAA guidelines, and by the 2030 agenda for the sustainable development. Strategies towards sustainability includes the use of native species, efficient use of feed and locally available resources, the level of control and monitoring over the production variables, technical qualification and infrastructure, and residue treatment (Boyd et al., 2020). Nevertheless, the current strategies are costly and sometimes unattainable by rural small farmers. Moreover, SARS-CoV-2, climate change and economic crises may increase the vulnerability of small farms, which demands innovative technologies in aquaculture that can adjust to these challenges and promote sustainability in the long term.

Brazilian aquaculture sector achieved economic relevance in the early 1980`s, and currently holds the 8th position in the ranking of major fish aquaculture producers, with >600 thousand tonnes produced in 2018 (FAO, 2020; Valenti et al., 2020). Lambari (*Astyanax spp*) is an indigenous fish group commercialized as live-bait, which culture is growing very fast in Brazil. Production attained ~1000 t, and lambari farms ranked at 5th in number of aquaculture properties in 2019 (Valenti et al., 2020). Lambari culture is comparable to most kinds of small-scale land-based fish culture in Brazil. Thus, its technical advantages and disadvantages may be an archetype of similar fish culture farms. Lambari is a group of native low-trophic level freshwater fish species widely distributed in Brazil, and its production was initially considered as a secondary product for additional income for small farmers in the southeast region. Due to the expansion of the live bait market for sport fishing in the region, lambari production has grown during the past decade. Its production occurs primarily in small aquaculture farms, operating in semi-intensive earthen pond systems (Fonseca et al., 2017), but the market expansion has attracted investors to implement larger farms (>20 ha) that operate under higher demand for infrastructure and energy.

Several different management practices are used in the farming of lambari (Fonseca et al., 2017). Producers settled their management choices empirically, or based on other species culture protocols. Inadequate management practices are often observed, since the amount of available scientific information and its access are insufficient to address the needs of most producers (Fonseca et al., 2017). As a result, some producers face low productivity, inefficient use of natural resources and generation of waste. Currently, lambari culture in Brazil ranges from farms with no technical support and low control of feeding regime, survival rate, and water flow to farms with qualified employees, monitoring equipment and indoor hatcheries. Nevertheless, the technology applied in all farms rarely relies on scientific-based information.

The absence of scientific-based protocols allied to the high variation in lambari culture currently practiced make it a good model to study the sustainability of different practices in freshwater fish culture. Furthermore, this situation claims for efforts in establishing more efficient and sustainable lambari farm systems. The assessment of the main aspects that drives sustainability would support the development of a scientific-based management towards more sustainable lambari production. Emergy synthesis is a useful tool for assessing bio-economic systems such as aquaculture (Agostinho et al., 2019; Bonilla et al., 2010; B.F. Giannetti et al., 2011). This method allows the evaluation of the work done by nature, society and economy on a common basis, identifying the main issues in a holistic way (Odum, 1996). Therefore, this study applies emergy synthesis to assess the sustainability of lambari aquaculture, providing a systemic perspective on the shortcomings of EAA related to the sustainability of small freshwater aquaculture. Additionally, management practices that negatively affect sustainability in semi-intensive pond freshwater systems were identified and more sustainable alternatives were proposed.

2. Materials and Methods

2.1. Data source and farms description

Nine lambari production farms were studied. They are located in the São Paulo State, Brazil (Figure 1), a subtropical region. Farms were selected with the assistance of the São Paulo State Rural Technical Assistance Agency. All farms produce the yellowtail lambari (*Astyanax lacustris*) in semi-intensive earthen ponds, intensively fed with commercial feed. Lambari farms differ for land and pond sizes, management strategies, and capital for economic investments in infrastructure and equipment. These dissimilarities resulted in the following three categories, or levels of control, according to systems technification degree: low control, moderate control, and high control (Table 1). The farms were grouped considering the breeding techniques used (natural, semi-natural or controlled), infrastructure and equipment available, control and monitoring of water quality and supplied feed, and survival rates. The process occurred according to the characteristics of production systems and was validated by regional experts in lambari production that work in the national rural offices.

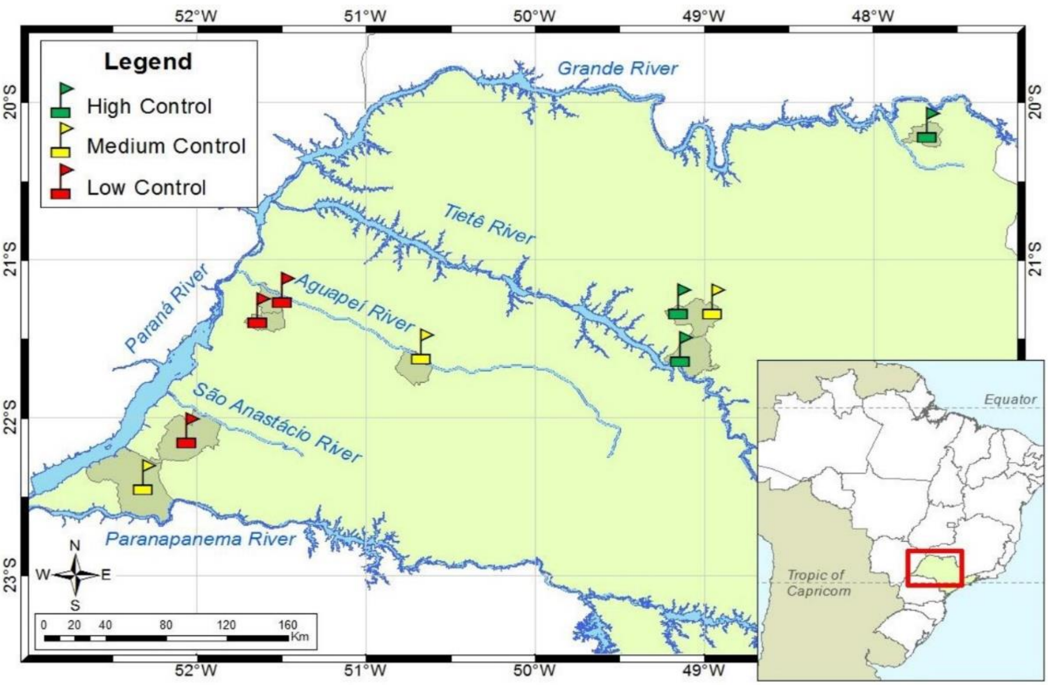

Figure 1. Location of the lambari aquaculture farms studied in the present work. High, medium and low control means a decreasing classification in the level of technification.

Data on natural and economic inputs, management practices and landscape features were obtained in situ, for each farm, through collecting samples of water, sediment, diet, and organisms that occurred in two visits at the beginning and end of one production cycle. Additional information was obtained through a semi-structured survey applied to the nine farmers in the beginning of the production cycle. The questionnaire focused on accounting for the total amount of materials, equipment, and infrastructure purchased, as well as labor, taxes, and depreciation. All inflows of materials, energy and money were accounted in unities/hectare, and they correspond to one year (i.e. 3 production cycles) of farm operation. Farmers validated the data collected at the end of the survey.

2.2. Emergy synthesis procedure

Data obtained from each farm were subjected to an emergy synthesis. Emergy is all the energy directly and indirectly used to generate a product or a service (Odum, 1996). This method is a biophysical approach based on a donor side perspective in establishing value for natural resources. Thus, it considers a holistic view, which recognizes all the effort done by nature in making available a resource. Moreover, as a donor side approach, emergy synthesis avoids the inherent subjectivities of the receiver side analysis, such as the life cycle assessment. The emergy synthesis procedure consists in three main steps: (i) elaborating the energy diagram by defining system's boundaries, input and output flows, and their relationship in internal processes (Figure 2); (ii) quantifying the main flows in the emergy accounting table (i.e. inventory), choosing suitable unit emergy values (UEVs), and calculating the emergy flows; (iii) calculating the emergy indicators to support comparisons and discussions. In the present study, the system boundaries were the same as the farm boundaries, including all local and external resources that sustain lambari aquaculture and their interaction within the production system. All input resources were classified as natural renewable resources (R), natural local non-renewable resources (N), or purchased resources from the economy (F). Input resources were accounted in mass (g), energy (J) or money (US$) units, and correspond to one year of farm operation, at one hectare farm basis, allowing comparisons between farms of different sizes.

Table 1. Characteristics of the evaluated lambari aquaculture systems. Low control (LC), moderate control (MC) and high control (HC) management levels. N/A = not available.

Production factors	LC	MC	HC
Breeding/spawning	Natural without control	Hormone-induced inside the pond	Hormone-induced controlled hatchery
Production cycle (months)	4	4	4
Crops/year	3	3	3
Pond area (ha)	<1.5	1.5 - 6.2	>6.0 ha
Fertilization regime	Poultry manure	Poultry manure	Poultry manure and/or chemical fertilizer
Stocking seed	larvae	larvae	juvenile
Stocking density - Nursery phase	N/A	N/A	250
Stocking density - Grow-out phase	~9	17-25	~30
Pond water exchange (%/day)	3.7	7.0	5.8
Water source	Spring water	Spring water	Superficial water
Diet protein content (%)	28	32-56	32-56
Survival (%)	N/A	N/A	56
Final fish length (mm)	80.0	93.3	96.6
Final fish weight (g)	10	16	18
Productivity (t/ha)	1.8	6.1	6.9

After quantified, the input resource flows were multiplied by their respective unit emergy values (UEVs), resulting in flows of the same unity: solar emjoules (sej). All UEV's used in this work (see Appendix A) were obtained from the scientific literature and the Emergy Evaluation Folios published by the Center of Environmental Policy from the University of Florida. The UEVs were updated to the global baseline of 1.20E+25 sej/yr (Brown and Ulgiati, 2016), and do not include labor and services, that were accounted separately as suggested by Ulgiati and Brown (2014). Additionally, the partial renewability values for each resource input were considered when available, as proposed by Agostinho et al. (2018). The sum of the emergy flows in solar emjoules (sej) results on the total emergy demanded (Y). Transformity is the UEV measured in sej/J, which is calculated by dividing the total emergy demanded in sej (input) by the total yield measured in joules (output). The emergy indices calculated in this work are presented in Table 2.

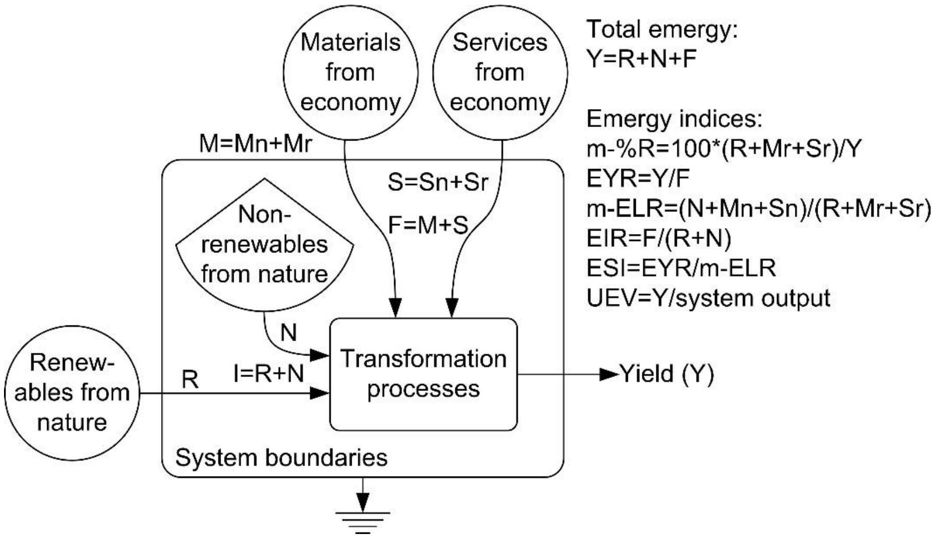

Figure 2. Generic energy diagram with symbols, acronyms and indicators used in emergy synthesis as presented in Table 2. Source: Agostinho et al. (2019).

Table 2. Emergy indicators used in the present study.

Emergy indicator	Algebra	Description
Unit emergy value	UEV = Y / E	Ratio of the total emergy demanded by the unity output. Example of units are sej/J, sej/kg and sej/$.
Renewability [a]	m-%R = 100 (R+Mr+Sr) / Y	Ratio of the nature and economy's renewable fraction by the total emergy demanded to produce lambari.
Environmental loading ratio [a]	m-ELR = (N+Mn+Sn) / (R+Mr+Sr)	Ratio of the total non-renewable resources by the total renewable resources.
Emergy yield ratio	EYR = Y / F	Ratio of the total emergy demanded to produce lambari by the resources from economy.
Emergy investment ratio	EIR = F / (R+N)	Ratio of the resources from economy by the nature's renewable and non-renewable resources.
Emergy sustainability index	ESI = EYR / m-ELR	Ratio between the emergy yield ratio by the environmental loading ratio.

Source: Odum (1996)
[a] Indicator modified according to Agostinho et al. (2018).

A resource is defined as renewable when its natural replenishment rate is higher than its extraction rate. In this study, the spring water withdraw rate for LC and MC farm was compared with the natural recharge rate of the regional aquifer, where the farm is located. The natural recharge rate for the regional aquifer is about 25-27% of the yearly rainfall per hectare (CPRM, 2012), which is approximately ten times lower than the farms' withdraw rate. Therefore, spring water input was assumed as a non-renewable resource demanded by aquaculture, as similarly considered by Cavalett et al. (2006), Wilfart et al. (2013), and Zhang et al. (2012, 2011). The UEV of fish feed was estimated (Appendix B) based on a diet formulated for lambari by Sussel et al. (2014).

2.3. Better scenario

. The variables seed production efficiency, water source, fertilization regime and protein and oil source in feed formulation are key inflows for fish productivity. Therefore, they were select to establish a better scenario for each lambari farm, wherein its effect on the emergy performance were further assessed. The practices that comprise the scenario are following described.

Practice 1. Improved seed productivity. This practice considers the introduction of substrates inside the ponds used for reproduction to protected newly hatched larvae for LC and MC farms. Lambari reproduction may be performed by hormone-induced spawning inside indoor tanks, which allows higher larvae productivity, fish size homogeneity, stocking density control, and survival rate (Felizardo et al., 2012) and should be maintained by HC farms. Nevertheless, the economic investment on infrastructure, equipment and qualified labor is often not affordable by the LC and MC farmers, even considering the higher profits. As an alternative, the introduction of substrates inside ponds for natural reproduction is a low-cost technique that reduces larvae losses (Rezende et al., 2005). Since LC and MC farms have lower control and monitoring of production, an increase in seed survival may result in a higher final productivity. Therefore, a 25% increase in productivity for the LC and MC systems is assumed as a plausible scenario as consequence of adopting this practice.

Practice 2. Changing water source. This practice includes the replacement of spring water by superficial water in the LC and MC systems, while the total water volume used remains the same. Therefore, the Unity Emergy Value (UEV) of the water source was replaced for LC and MC farms in the emergy accounting table (see Appendix A). The HC farms consumes superficial water, thus, this practice should be conserved.

Practice 3. Controlling pond fertilization. Fish nutrition is improved by the intake of organisms from the natural biota existing inside ponds. Chemical or organic fertilizers are inputs commonly applied in fish farms, but usually under improperly techniques that leads to inefficiency. To support natural food production, the empirical practices as currently performed by farmers is replaced by a controlled fertilization protocol. This practice establishes the use of 90 kg/1000m²/yr of lime, 56 kg/1000m²/yr of manure, 6.3 kg/1000m²/yr of urea and 2.3 kg/1000m²/year of phosphorus, as suggested by Pucher et al. (2014), and is accounted for all lambari farms.

Practice 4. Replace fish meal protein and fish oil by vegetable protein and oil sources. This practice considers the total replacement of animal protein by vegetable sources in commercial feed, following a diet formulated by Sussel et al. (2014) for lambari. Currently, commercial feed used in lambari aquaculture relies on high protein contents that derives from animal sources, such as marine fish meal and oil, and livestock byproducts such as viscera, feather, and bones. Other components of commercial feed are mainly soy and corn. Fish oil and fishmeal are environmentally costly as their consumption causes a pressure on the natural stocks of marine fish. In addition, a diet that do not match the target fish requirements will increase nutrient wastes in the effluents and consequently cause eutrophication in receiving body of waters (Boyd et al., 2007; Flickinger et al., 2019b). Since lambari is a low-trophic level fish, the use of vegetable protein sources rather than animal ones is a feasible alternative that does not affects productivity (Sussel et al., 2014).

2.4. Approaches for results analysis

Results analysis followed three approaches: (i) emergy index-by-index comparison among the assessed nine-lambari farms considering the current and the simulated scenario practices; (ii) the use of emergy ternary diagram; (iii) Emergy sustainability index and global efficiency graph (ESI-UEV). The second and third methods are explained as follows. The ternary diagram is an equilateral triangle, which the three corners represent each emergy sources (R, N and F). Thus, any system plotted in the diagram is represented by a point, in which R, N and F can be determined by reading from zero along the basal line (axis) at the bottom of the diagram to 100% at the vertex of the triangle (see Bonilla et al.,2010 and Giannetti et al., 2011 for details). The emergy ternary diagram allows a visual comparison between systems in terms of proportion for R, N and F emergy flows, and spatial representation of system emergy performance (Almeida et al., 2007; Giannetti et al., 2006). Besides lambari real and scenario data, nine different aquaculture systems assessed under the emergy synthesis were obtained from the literature for further comparison. In the ESI-UEV graph, emergy sustainability indicator (ESI) and efficiency (the inverse of UEV) data for each lambari system were plotted on a two-axis graph, in which larger ESI x UEV area represents higher performance. Sustainability can be defined as an optimum balance between resilience and efficiency (Byrne, 2016). The emergy sustainability index (ESI, accounts for the total environmental pressure of the system over the biosphere capacity (a viewpoint of environmental resilience), and global efficiency (or inverse UEV) measures how efficient a system is for converting the emergy inflow into a product. Therefore, this graph aims to represent which lambari system have the best balance of both.

3. Results

3.1. Lambari production under current practices

The energy system diagram (Figure 3) shows the lambari production features under the systemic view of emergy synthesis. Most of the energy flows comes from outside the farms boundaries, such as sun, rain, commercial feed, equipment, materials and labor. All the lambari aquaculture systems evaluated in this study rely on similar external inputs and internal processes, in which the differences are related to the amount and proportions for R, N and F input resources demanded by each farm. Besides, the high (HC) and moderate (MC) control level systems rely on external labor either permanent or eventual, while the low control (LC) system relies on local family labor. Energy flows interact within system boundaries with internal stocks of natural capital, hatchery (in the HC farms), and the pond, allowing the production of lambari fish as the main output. Environmental services are co-products and effluents are sub-products produced at different rates among farms. Overall, farms with lower control over the production – divergent practices from the established by scientific-technical protocols – and lower productivity demand lower emergy per hectare compared to the farms with higher control (Table 3). The main inputs for the LC systems are services (27-46%), feed (7-39%) and water (15-21%), while for the MC farms, the main inputs are feed (35-49%) and services (33-39%), and for HC farms, the main flows are feed (17-48%) and services (26-36%). Unrelated to the management control level, all systems depend mostly on non-renewable sources, as purchased inputs F are responsible for more than 60% of the total emergy required (Table 3).

The emergy indicators showed a random pattern among the evaluated farms (Tables 4, 5 and 6).. The HC1 farm shows the worst performance for UEV, achieving a value approximately 5 times higher than the farm with the best performance (HC2) (Table 6). The HC2 shows the best overall emergy performance among the studied farms, including the highest renewability (m-%R) and sustainability (ESI) and the lowest environmental loading (ELR) and emergy investment ratios (EIR). As well, EIR seems slightly lower in the LC farms (Table 4) compared to MCs and HC1 and HC3. Anyhow, all the lambari farms studied are strongly dependent on F resources, which means a low contribution to the larger economy (EIR > 1), and show an emergy sustainability index (ESI) bellow 1, which is an indicative of unsustainable systems.

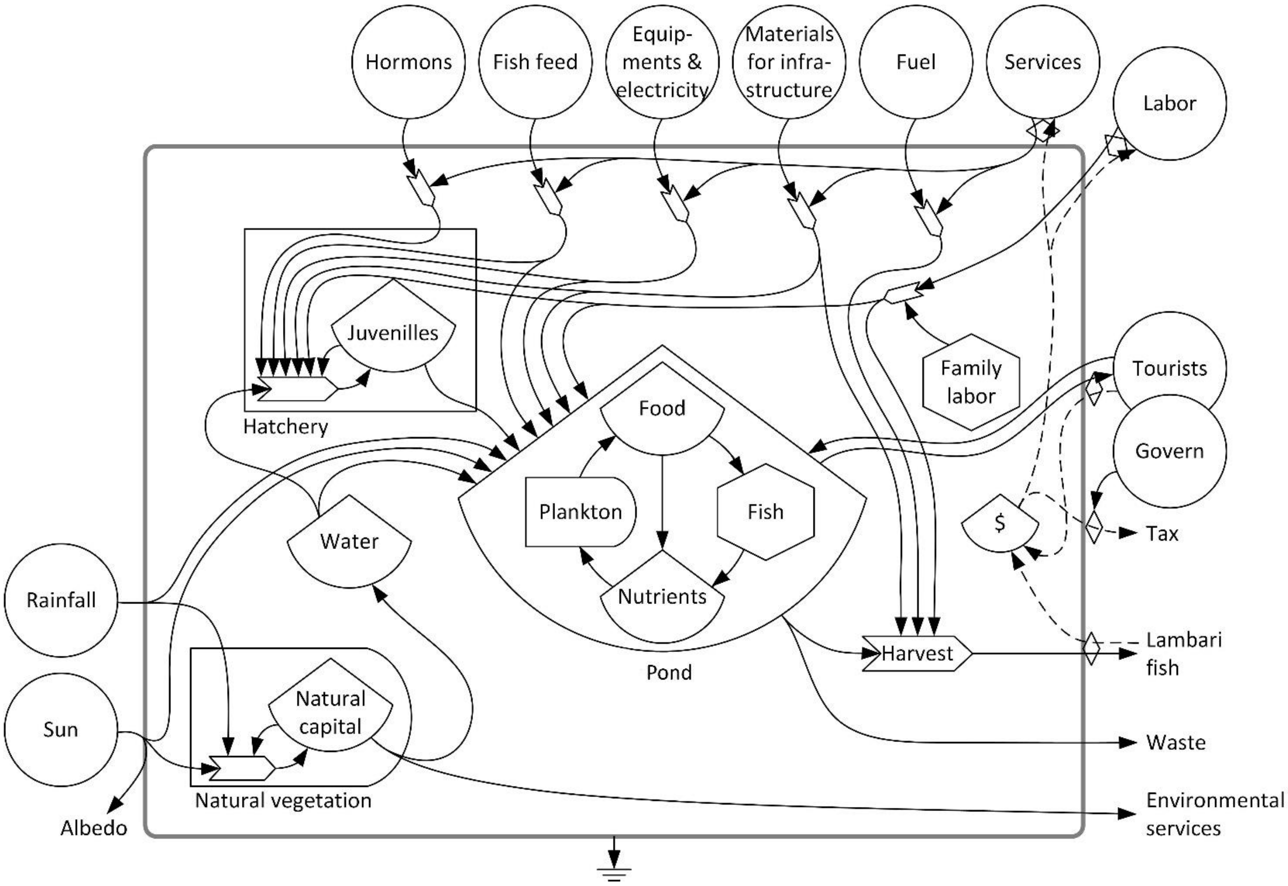

Figure 3. Energy diagram of lambari aquaculture production systems. Hatchery "box" is present only in high control farms (HC). Arrows represent energy flows, circles represents the outside sources, stocks are represented by tanks, and energy transformation processes represented by the interaction symbol; dashed arrows represent monetary flows; outputs are the harvested lambari, water effluent and environmental services. Symbol details in Odum (1996).

Table 3. Emergy accounting results in sej/ha/yr for the nine evaluated lambari aquaculture systems in Brazil. Low control (LC), moderate control (MC) and high control (HC) management levels. Numbers (1, 2 and 3) are the identification of different farms within a same control level. R, renewable resources from nature. N, non-renewable resources from nature. F, resources from the larger economy. Emergy columns presents the emergy flow from each item for each farm. Percentage columns (%) presents the emergy fraction of an item relative to the total emergy (Y) for each farm.

Item	LC1		LC2		LC3		MC1		MC2		MC3		HC1		HC2		HC3	
	Emergy	%	Emergy	%	Emergy	%	Emergy	%	Emergy	%	Emergy	%	Emergy	%	Emergy	%	Emergy	%
Sun (R)	4.67E+13	<1	4.67E+13	<1	4.67E+13	<1	4.67E+13	<1	4.67E+13	<1	4.67E+13	<1	4.67E+13	<1	4.67E+13	<1	4.67E+13	<1
Rainfall (R)	2.12E+15	3	2.12E+15	2	2.12E+15	3	2.12E+15	1	2.12E+15	1	2.12E+15	1	1.36E+15	<1	1.99E+15	2	1.36E+15	1
Superficial water (R)	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	1.17E+16	3	1.42E+16	17	1.08E+16	4
Soil occupation (N)	1.22E+15	2	8.01E+14	1	3.87E+14	1	3.33E+15	1	1.43E+15	1	2.10E+15	1	2.10E+16	5	3.30E+15	4	1.18E+15	<1
Groundwater (N)	1.41E+16	21	2.44E+16	19	1.03E+16	15	1.41E+16	5	1.48E+16	10	1.46E+16	9	0.00E+00	0	0.00E+00	0	0.00E+00	0
Feed (F)	4.77E+15	7	4.95E+16	39	1.87E+16	27	1.26E+17	49	5.43E+16	35	5.89E+16	37	2.19E+17	48	2.63E+16	31	4.02E+16	17
Equipment (F)	1.12E+13	<1	7.27E+14	1	2.13E+13	<1	1.20E+15	<1	1.38E+14	<1	5.25E+14	<1	2.69E+14	<1	1.80E+13	<1	5.89E+15	2
Electricity (F)	9.82E+12	<1	7.24E+14	1	1.92E+13	<1	1.20E+15	<1	1.38E+14	<1	5.21E+14	<1	2.69E+14	<1	1.80E+13	<1	5.89E+15	2
Infra-structure (F)	3.67E+12	<1	5.25E+12	<1	4.09E+12	<1	6.08E+12	<1	2.36E+12	<1	8.52E+12	<1	8.57E+12	<1	1.50E+12	<1	8.73E+12	<1
Lime (F)	4.66E+15	7	4.66E+15	4	4.66E+15	7	4.66E+15	2	4.66E+15	3	4.66E+15	3	4.66E+15	1	4.66E+15	6	4.66E+15	2
Organic fertilizer (F)	9.21E+15	13	9.21E+15	7	9.21E+15	13	9.21E+15	4	9.21E+15	6	9.21E+15	6	9.21E+15	2	9.21E+15	11	9.21E+15	4
Fuel (diesel) (F)	4.98E+14	1	8.62E+14	1	4.88E+14	1	7.32E+15	3	2.36E+15	2	8.79E+15	6	6.10E+15	1	1.46E+15	2	5.58E+16	23
Labor (F)	0.00E+00	0	4.76E+14	<1	0.00E+00	0	6.48E+15	3	5.22E+15	3	6.27E+15	4	1.70E+16	4	1.16E+15	1	2.93E+16	12
Services (F)	3.16E+16	46	3.40E+16	27	2.43E+16	35	8.41E+16	33	6.09E+16	39	5.16E+16	33	1.66E+17	36	2.15E+16	26	8.13E+16	34
Total emergy (Y)	6.83E+16		1.27E+17		7.02E+16		2.59E+17		1.55E+17		1.59E+17		4.57E+17		8.38E+16		2.40E+17	
Total (R) [a]	8.25E+15	13	1.18E+16	9	8.23E+15	12	2.44E+16	9	164E+16	11	1.56E+16	10	5.32E+16	12	2.24E+16	27	3.62E+16	15
Total (N)	1.54E+16	23	2.52E+16	20	1.07E+16	15	1.74E+16	7	1.63E+16	10	1.63E+16	11	2.10E+16	5	3.30E+15	4	1.18E+15	<1
Total (F)	4.43E+16	65	8.98E+16	71	1.07E+16	73	2.17E+17	84	1.23E+17	79	1.627E+17	80	3.82E+17	84	5.81E+16	69	2.02E+17	84

[a] Includes the flows of Sun, Rainfall, Superficial water and the renewable fraction from N and F flows.

Table 4 Emergy indicators for the current management and the better scenario of lambari aquaculture low control farms. Current low control (LC) and better scenario for low control (LC’). Numbers (1, 2 and 3) are the identification of each different farm within a same control level. UEV = Unity emergy value; m-%R = renewable fraction; m-ELR = Environmental loading ratio; EYR = Emergy yield ratio; EIR = Emergy investment ratio; ESI = Emergy sustainability ratio.

Indicator	LC1	LC1’	LC2	LC2’	LC3	LC3’
UEV (E6 sej/J)	2.84	1.86	1.89	1.21	3.07	1.90
UEV (E10 sej/g)	4.88	3.19	4.23	2.72	7.02	4.34
UEV (E6 sej/J)*	1.53	0.79	1.38	0.80	2.01	1.04
UEV (E10 sej/g)*	2.62	1.37	3.09	1.79	4.59	2.37
m-%R (%)	13	37	9	33	12	31
m-ELR	6.9	1.7	9.8	2.0	7.5	2.2
EYR	1.3	1.4	1.3	1.3	1.2	1.3
EIR	3.9	3.4	4.6	4.0	5.5	4.5
ESI	0.2	0.8	0.1	0.7	0.2	0.6

* without services.

Table 5. Emergy indicators for the current management and the better scenario of lambari aquaculture moderate control farms. Current moderate control (MC) and better scenario for moderate control (MC’). Numbers (1, 2 and 3) are the identification of each different farm within a same control level. UEV = Unity emergy value; m-%R = renewable fraction; m-ELR = Environmental loading ratio; EYR = Emergy yield ratio; EIR = Emergy investment ratio; ESI = Emergy sustainability ratio.

Indicator	MC1	MC1’	MC2	MC2’	MC3	MC3’
UEV (E6 sej/J)	1.55	1.02	0.91	0.61	2.17	1.44
UEV (E10 sej/g)	3.38	2.23	2.07	1.38	5.09	3.38
UEV (E6 sej/J)*	1.05	0.62	0.55	0.32	1.46	0.32
UEV (E10 sej/g)*	2.28	1.35	1.26	0.18	3.44	0.18
m-%R (%)	9	17	11	23	10	22
m-ELR	9.6	4.8	8.5	3.4	9.2	3.6
EYR	1.1	1.1	1.1	1.2	1.1	1.2
EIR	13.2	11.5	8.4	7.4	8.4	7.4
ESI	0.1	0.2	0.1	0.3	0.1	0.3

* without services.

Table 6. Emergy indicators for the current management and the better scenario of lambari aquaculture high control farms. Current high control (HC) and better scenario for high control (HC'). Numbers (1, 2 and 3) are the identification of each different farm within a same control level. UEV = Unity emergy value; m-%R = renewable fraction; m-ELR = Environmental loading ratio; EYR = Emergy yield ratio; EIR = Emergy investment ratio; ESI = Emergy sustainability ratio.

Indicator	HC1	HC1'	HC2	HC2'	HC3	HC3'
UEV (E6 sej/J)	4.68	2.54	0.86	0.55	2.47	1.81
UEV (E10 sej/g)	10.3	5.62	2.09	1.33	4.97	3.63
UEV (E6 sej/J)*	2.97	1.45	0.64	0.37	1.63	1.13
UEV (E10 sej/g)*	6.58	3.20	1.56	0.89	3.28	2.27
m-%R (%)	12	14	27	32	15	16
m-ELR	7.6	6.3	2.7	2.1	5.6	5.2
EYR	1.1	1.1	1.3	1.4	1.1	1.1
EIR	13.4	11.4	4.3	3.4	18.0	16.4
ESI	0.1	0.2	0.5	0.7	0.2	0.2

* without services

The ternary diagram (Figure 4a) shows the emergy performance of the nine evaluated lambari farms, compared with nine other aquaculture systems data obtained from literature. All systems are located very close to each other and to the F vertex, indicating a dependence on purchased resources (> 63%), which leads to an overall unsustainable performance (ESI<1).

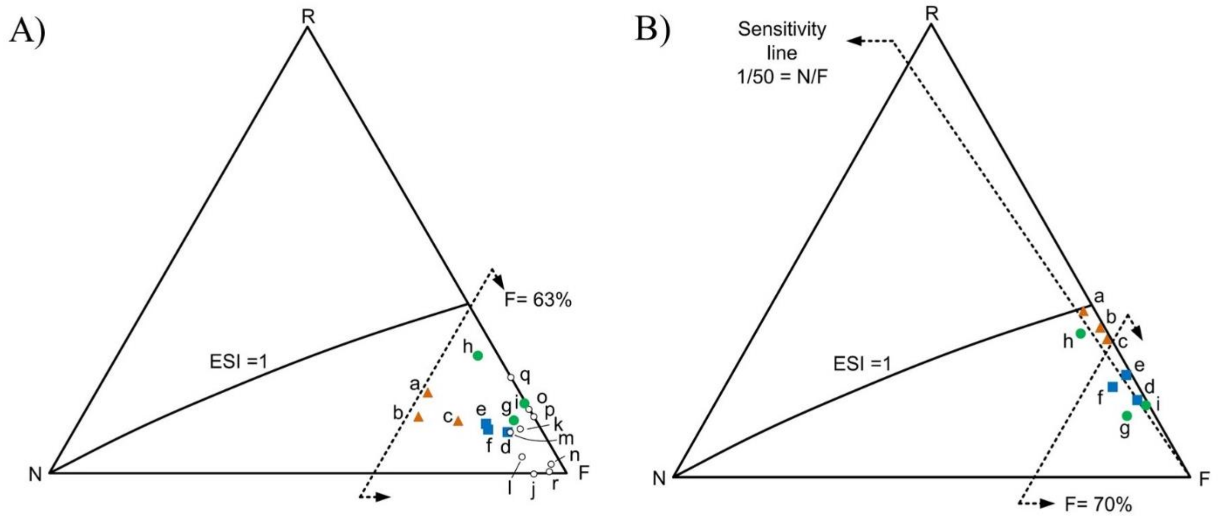

Figure 4. A) Ternary emergy diagram representing the proportions of renewable resources (R), non-renewable resources (N) and resources from economy (F). Evaluated lambari aquaculture systems in the present study were represented by▲, ●, and ■; data from literature were represented by ○. ESI = emergy sustainability index. a = LC1; b = LC2; c = LC2; d = MC1; e = MC2; f = MC3; g = HC1; h = HC2; i = HC3; j = recirculating aquaculture system, k = extensive pond system, and l = semi-extensive system from Wilfart et al. (2013); m = integrated pig-grains-fish culture and n = semi-intensive fish pond system from Cavalett et al. (2006); o = semi-intensive fish pond from Cheng et al. (2017) ; p = net-cage intensive system and q = net-cage intensive system + bamboo substrate from David et al. (2018); r = intensive fish pond from Zhang et al. (2011). B) Ternary diagram representing the proportions of renewable resources (R), non-renewable resources (N) and resources from economy (F) for lambari aquaculture systems after the simulated scenarios for better management practices. Legend: LC systems (▲); MC systems (■); HC systems (●); ESI = emergy sustainability index. A = LC1'; b = LC2'; c = LC3'; d = MC1'; e = MC2'; f = MC3'; g = HC1'; h = HC2'; i = HC3'.

3.2 Better scenario

The simulated BMPs lead to an improvement of emergy performance for all evaluated lambari farms, including higher renewability and efficiency, while reducing the environmental loading ratio. The LC systems achieved the greatest improvements for renewability (between 164 and 255% increase), while reducing the ELRs (between 71 and 80% decrease) and transformities (between 35 and 38% decrease) (Table 4). The MC (Table 5) and HC (Table 6) systems obtained an increase for renewability (in a range of 81-124% and 6-20% of increase, respectively), and reduced their ELRs (in a range of 50-61% and 7-23% of reduction) and transformities (in a range of 27-46% of reduction). Likewise, the ESI for all farms were increased (LC increase of >269% from 0.2 to 0.7; MC between 78-142% from 0.1 to 0.3, and HC between 6-47% from 0.1 to 0.2 for HC1 and HC3, and from 0.5 to 0.7 for HC2). Although the BMPs resulted in better emergy performance, all the evaluated farms still remain below the ESI=1 line and, therefore, they are considered unsustainable.

As the proportions of R, N and F emergy flows changed after the simulated BMPs, the spatial position of all farms also changed in the ternary diagram (Figure 4). Farms LC1', LC2', LC3' and HC2' moved closer to the ESI=1 line compared to their relative position before applying BMPs (Figure 4), as the proportion of renewable resources was increased. Although increasing their renewability ratios (m-%R), the farms MC1', MC2', MC3', HC1' and HC3' position remain distant from the ESI=1 and close to F vertex, resulted from the high dependence (>70%) on F resources. A sensitivity line indicates that emergy sustainability for the lambari production systems is improved by going in direction of R vertex, but the proportion of 1/50 between N and F resources keeps approximately the same. When more data becomes available, further studies can be developed to verify this tendency.

The Figure 5 indicates the systems with better performance for ESIxUEV balance. Three aspects deserves attention: (i) the simulated BMPs resulted in higher performance for all the evaluated systems; (ii) the LC systems achieved the highest improvement, as a result of the management improvements scenario; (iii) the system with the best balance of higher efficiency and environmental sustainability was the HC2', followed by LC2', MC2', HC2, LC1', LC3', MC1', MC3', MC2, HC3', HC3, HC1', MC1, LC2, LC1, MC3, LC3, HC1 in an hierarchical order.

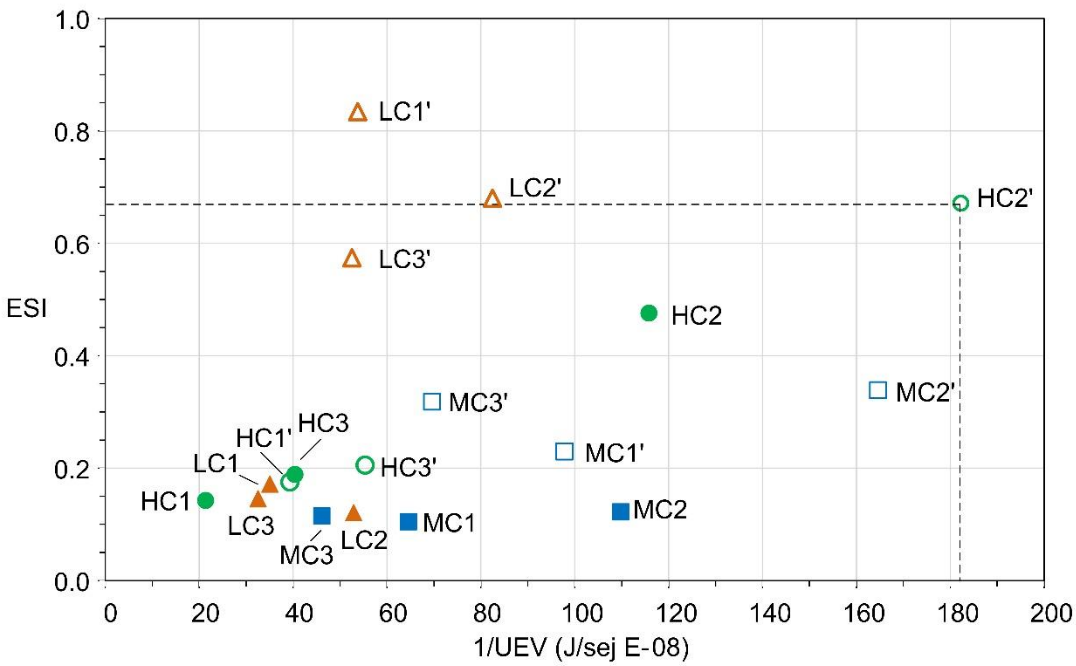

Figure 5. Emergy sustainability index (ESI) and global efficiency (inverse of unit emergy value) for the current management and proposed scenarios for the lambari production farms evaluated. Higher area means higher performance. The dashed line represents the area of the system with higher performance. LC = ▲; LC' = △; MC = ■; MC' = □; HC = ●; HC' = ○. Different colors represent different farms within the same management level: orange = low control; blue = moderate control; green = high control.

4. Discussion

The lambari aquaculture systems evaluated in this study are dependent on similar resources. Despite the existing similarities, farms show different emergy performances for efficiency, renewability, environmental pressure and nature's investment, regardless of their level of management control. The farms with higher control level (HC) achieved higher productivity. Nevertheless, they are the most dependent on resources from the larger economy (F). The HC2 farm had the best performance for all emergy indicators, surpassing HC1 and HC3 although they have the same control level. The HC2 consumes lower amount of commercial feed emergy (sej/ha/year) than HC1, more organic fertilizers than HC1 and HC3 and reaches similar productivity than both. Therefore, HC2 represent a system with more effective use of natural food. Conversely, the LC farms have the lowest productivity and consume higher volumes of spring water per hectare, which is a local non-renewable resource (N), leading to lower emergy performance. These findings imply that, when higher the level of management control, higher the farm productivity but not necessarily higher emergy performance or sustainability. For the evaluated farms under the current practices, feeding regimes and water management appears as key aspects for the emergy sustainability of lambari production. However, none farm achieved ESI higher than 1, indicating that all remain unsustainable production systems under the emergy view.

Commercial feed has been reported as the main emergy flow for fish production systems (David et al., 2018; Garcia et al., 2014; Odum, 2000; Zhang et al., 2011). Intensive feeding regimes may lead to a higher productivity, but large amounts of the commercial feed consumed flows out with the water effluent, causing eutrophication in the surrounding water streams (Boyd et al., 2020), or remain accumulated in pond bottom (David et al., 2017a, 2017b; Flickinger et al., 2020, 2019b, 2019a) causing issues to pond management. The inefficient use commercial feed also cause the depletion of natural stocks of fish shoals and other resources (soybean, corn, etc.) that sustain commercial feed production (Ahmed et al., 2019; Boyd et al., 2007). In the extreme opposite situation, those fish culture systems that demands lower amount (< 20% of total emergy) or even do not use commercial feed are recognized as unproductive and economically unfeasible (Wilfart et al., 2013; Zhang et al., 2011). These unfed fish farms require larger land areas and rely on chemical and organic fertilizers for natural food production in the water ponds, which are their highest emergy input flow (Zhang et al., 2012). Our results reinforces that fish feeding practice is environmental costly and deserves attention for improvements. As an alternative, the replacement of fish meal and oil by vegetal protein and oil sources is suggested for the culture of omnivorous species such as lambari (Sussel et al., 2014), which would lead to a reduction of 27% in the feed emergy flow. The results obtained in the present study suggest that replacing animal raw materials by vegetal ones in the feed industry leads towards higher emergy sustainability for fish production.

Water is another expressive emergy input flow for the evaluated LC and MC systems. This high emergy value results from the large volumes demanded added to the high UEV value for spring water. Climate change may affect water availability in near future, increasing the risk of local conflicts triggered by water demand (Ahmed and Thompson, 2019; Jamalimoghaddam et al., 2019). Extreme weather events, such as droughts, are expected to occur in higher frequency and intensity. These events threatens groundwater stocks level and total fresh water availability, causing production loss (Ahmed et al., 2019). Most of lambari producers are considered small farmers, with low access to capital or technology to deal with the environmental threats and social conflicts. Considering this scenario, the replacement of spring water by superficial water sources improves the systems resilience

(Figure 5). Additionally, under a systemic perspective of the farms, producers could make use of the high nutrient water stored within the ponds as fertilizers for the production of fruits and vegetables within farms (Bosma and Verdegem, 2011), since many small farms diversify their crops for subsistence and additional income.

The urgency for sustainable production systems is a well-established global concern (United Nations, 2015), in which the challenge is how to combine the constant increasing demand for highly productive systems within Earth's biocapacity. Systems traditionally known as highly productive, such as the intensively fed monocultures, are strongly dependent on fossil energy, a non-renewable resource. Conversely, the so-called extensive systems use more space and do not take full advantage of the available free natural resources, failing in competing with those intensive systems that are more efficient. Therefore, the idea of sustainability as a contingent balance of efficiency and resilience seems to be more effective than a linear advance towards a static state (Byrne, 2016). Thus, combining emergy sustainability (ESI) with efficiency (inverse UEV), as shown in Figure 5, provides a better image of the sustainability path of the assessed lambari systems.

Although sustainability is context-dependent and requires constant adaptation, the HC2 farm showed most successful balance of emergy sustainability and efficiency among all the evaluated fish production systems under current practices. Moreover, the simulated scenario for BMPs showed improvements for all systems. This indicates that aquaculture technologies designed with an ecological approach are likely to succeed on the long term, as they can achieve higher performance through simple and feasible changes in their management procedures. As one example, integrated multi-trophic aquaculture (IMTA) is a framework that allows the culture of aquatic species from different trophic levels and with complementary ecosystem functions (Ridler et al., 2007). IMTAs goal is to increase the productivity by using the uneaten feed, wastes, and considering by-products as fertilizers and feed as energy sources for other crops, taking advantage of the synergistic interactions among species (Flickinger et al., 2019b; Franchini et al., 2020). For a more sustainable fish production, systems dependence on fossil energy must be reduced at the same time their productivity is increased, and this can be achieved by more ecologically driven and integrated production systems.

All lambari production systems evaluated in this work uses similar kinds of external resources; nevertheless, lack of efficiency and dependence on F resources affects their emergy performance. The access of high quality information from technology-transfer and research centers is important to increase productivity under lower consumption of non-renewable resources. Accurate staff training, technical assistance, personal relationship between the aquaculture producers and research institutes, organization of producers in cooperatives or associations, and effective government regulation are key factors towards a more sustainable aquaculture systems (Boyd et al., 2020; Henares et al., 2019). When the ‘information input’ is neglected or inappropriately used, the system operates inefficiently. Although hardly accounted, information is a costly emergy input for many kinds of natural and human systems, but its use guarantees systems self-organization capacity towards higher emergy efficiency (Odum, 1996). In the Brazilian aquaculture sector, the information sharing process has been underrated, which has led to inefficient production systems, resulting in high environmental pressures and low economic returns (Henares et al., 2019). Therefore, technology transfer is a strategic step, perhaps the most important one, towards more sustainable fish production systems.

5. Conclusion

All lambari production systems studied rely mostly on non-renewable resources, mainly on commercial feed and water, regardless of the control level (low, moderate or high). The emergy performance of all farms were similar, with slight advantage for the high control (HC) farm #2. This variation may be a result of accessibility to high-quality information on production management. Excepted by HC farm #2, the low renewability (m-%R<15%), high environmental load (ELR>5.6) and low emergy yield ratio (EYR<1.3) indicates that the systems are unsustainable (ESI<0.2). Nevertheless, a scenario ofsimple and feasible management practices including water-source change, control of pond fertilization, increase of productivity by breeding management, and the exchange of animal protein and oil sources by vegetal ones, results in higher emergy performance for all farms. Although the emergy sustainability of the proposed scenario is still low (ESI<0.8) due to the high demand for purchased resources (EYR<1.4), their renewability increased (m-%R<33%) along with a reduction of the environmental loading ratio (ELR>1.7), indicating that the proposed practices provide benefits under an emergy perspective. Additionally, the scenario increased systems resilience ,expressed by the emergy sustainability index x global efficiency (ESIxUEV) relationship. Efforts are still needed towards better management practices on the lambari aquaculture production, but the findings of this work highlight that simple changes make a difference on the sustainability of small-scale inland aquaculture. This conclusion is strengthened by the use of the emergy synthesis, which is a holistic approach in assessing sustainability that recognizes the effort of nature in providing resources.

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Appendix A. Inventory and unit emergy values (UEV) for the nine evaluated lambari production systems. Legend: Low control (LC), moderate control (MC) and high control (HC) management levels. Numbers (1, 2 and 3) represent different farms within the same control level. R, renewable resources from nature; N, non-renewable resources from nature; F, resources from the larger economy; %R, renewability fraction in %. Calculation details in the Supplementary Material.

Item and its classification	Unit	UEV [a] (sej/Unit)	Reference for UEV	%R	Amount in Unit/ha/yr								
					LC1	LC2	LC3	MC1	MC2	MC3	HC1	HC2	HC3
1. Sun (R)	J	1.00E+00	Odum, 1996	100	4.67E+13	4.67E+13	4.67E+13	4.67E+13	4.67E+13	4.67E+13	4.67E+13	4.67E+13	4.67E+13
2. Rainfall (R)	J	2.31E+04	Odum, 1996	100	9.16E+10	9.16E+10	9.16E+10	9.16E+10	9.16E+10	9.16E+10	9.16E+10	9.16E+10	9.16E+10
3. Superficial water (R)	J	5.23E+04	Comar, 2001	100	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4. Soil occupation (N)	J	9.42E+04	Brandt-Williams, 2002	0	1.30E+10	8.50E+09	8.50E+09	8.50E+09	1.52E+10	1.52E+10	1.52E+10	1.52E+10	1.52E+10
5. Springwater (N)	J	5.63E+04	Buenfil, 2001	0	2.51E+11	4.34E+11	4.34E+11	4.34E+11	2.63E+11	2.63E+11	2.63E+11	2.63E+11	2.63E+11
6. Feed (F)	g	7.01E+09	Appendix B	5	6.80E+05	7.06E+06	7.06E+06	7.06E+06	7.74E+06	7.74E+06	7.74E+06	7.74E+06	7.74E+06
7. Equipment (F)													
7.1 Iron	g	7.63E+10	Buranakarn, 1998	0	3.40E+00	5.88E+00	3.33E+00	2.00E+01	1.61E+00	4.96E+01	8.33E+00	3.75E-01	2.00E+01
7.2 Plastic	g	3.90E+09	Buranakarn, 1998	0	3.82E+00	1.36E+01	6.69E+00	2.21E+01	4.69E+00	5.39E+01	1.73E+01	1.25E+00	1.93E+01
7.3 Steel	g	5.92E+09	Brown and Ulgiati, 2004	0	1.79E+02	4.95E+02	3.02E+02	1.08E+01	5.81E-01	2.67E+01	1.08E+01	1.33E+00	1.08E+01
7.4 Aluminum	g	1.62E+10	Buranakarn, 1998	0	6.80E-03	1.00E-02	6.67E-03	3.30E-01	1.61E-03	8.18E-01	3.30E-01	3.95E-03	3.30E-01
7.5 Glass fiber	g	1.00E+10	Buranakarn, 1998	0	0.00E+00	0.00E+00	0.00E+00	7.00E-01	0.00E+00	1.74E+01	2.33E+00	3.85E-02	7.00E+00
8. Electricity (F)	J	1.11E+05	Giannetti et al., 2015	68	8.82E+07	6.50E+09	1.72E+08	1.08E+10	1.24E+09	4.67E+09	2.41E+09	1.62E+08	5.28E+10
9. Infrastructure (F)													
9.1 Copper	g	7.43E+10	Cohen et al., 2007	0	3.13E-01	5.41E-01	3.07E-01	0.00E+00	1.47E-01	2.72E-01	1.01E+00	7.77E-02	1.06E+00
9.2 Bricks	g	2.79E+09	Buranakarn, 1998	0	1.31E+03	1.87E+03	1.46E+03	2.18E+03	8.41E+02	3.05E+03	3.05E+03	5.37E+02	3.10E+03
10. Lime (F)	g	1.24E+09	Odum, 1996	0	3.75E+06	3.75E+06	3.75E+06	3.75E+06	3.75E+06	3.75E+06	3.75E+06	3.75E+06	3.75E+06
11. Organic fertilizer (F)	g	3.07E+09	Castellini et al., 2006	16	3.00E+06	3.00E+06	3.00E+06	3.00E+06	3.00E+06	3.00E+06	3.00E+06	3.00E+06	3.00E+06
12. Fuel (diesel) (F)	J	1.37E+05	Brown et al., 2011	0	3.63E+09	6.28E+09	6.28E+09	6.28E+09	1.72E+10	1.72E+10	1.72E+10	1.72E+10	1.72E+10
13. Labor (F)	$	3.23E+12	Giannetti et al., 2018	15	0.00E+00	1.48E+02	1.48E+02	1.48E+02	1.62E+03	1.62E+03	1.62E+03	1.62E+03	1.62E+03
14. Services (F)	$	3.23E+12	Giannetti et al., 2018	15	3.40E+03	1.24E+03	1.24E+03	1.24E+03	9.79E+03	9.79E+03	9.79E+03	9.79E+03	9.79E+03

[a] UEVs updated to the 1.20E25 sej/yr emergy baseline without accounting for labor and services.

Appendix B. Unit emergy value (UEV) estimation for lambari commercial feed. The amount of ingredients relate to 1g of commercial feed and based on Sussel et al. (2014). %R = renewability fraction in %.

Item	Unit	UEV[a] sej/Unit	Amount (Unit)	%R	Renewable emergy flow (sej)	Non-renewable emergy flow (sej)	Total emergy (sej)	Reference for UEV
Rice bran	g	9.70E+08	0.09	0	0.00E+00	8.73E+07	8.73E+07	Brown and McClanahan, 1996
Corn bran	g	1.45E+10	0.26	0	0.00E+00	3.77E+09	3.77E+09	Brandt-Williams, 2002
Soybean meal	g	3.35E+09	0.2	30	1.99E+08	4.71E+08	6.70E+08	Takahashi and Ortega, 2010
Cottonseed meal	g	4.01E+09	0.09	17	6.12E+07	3.00E+08	3.61E+08	Takahashi and Ortega, 2010
Wheat bran	g	1.09E+09	0.2	22	4.88E+07	1.69E+08	2.18E+08	Dong et al., 2008
Poultry viscera meal	g	4.05E+09	0.0325	16	2.11E+07	1.11E+08	1.32E+08	Castellini et al., 2006
Meat and bone meal	g	4.64E+10	0.027	0	0.00E+00	1.25E+09	1.25E+09	Brandt-Williams, 2002
Fishmeal	g	3.13E+09	0.0175	50[b]	2.73E+07	2.73E+07	5.47E+07	Brown and Bardi, 2001
Blood meal	g	4.64E+10	0.01	0	0.00E+00	4.64E+08	4.64E+08	Brandt-Williams, 2002
Total					3.57E+08	6.65E+09	7.01E+09	

[a] UEVs updated to the 1.20E25 sej/yr emergy baseline without accounting for labor and services.

[b] The Brazilian sardinella (*Sardinella brasiliensis*) is one of the sardine species used as a protein source ingredient in animal feed composition. FAO suggests that excessive fishing pressure could exacerbate biomass declines and delay or compromise potential natural recoveries (available at: http://firms.fao.org/firms/resource/13329/en). Therefore, we assumed a 50% renewability for the fishmeal flow due to its current overexploitation.

CAPÍTULO 2: Ecosystem functions in pond aquaculture and their roles in providing ecosystem services and disservices

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Ecosystem functions in pond aquaculture and their roles in providing ecosystem services and disservices

Tamara Fonseca[a]; Feni Agostinho[b]; Biagio F. Giannetti[b]; Wagner C. Valenti[a,c] .

[a] Aquaculture Center, São Paulo State University (UNESP), Brazil.
[b] Post-graduation Program on Production Engineering, Paulista University (UNIP), Brazil.
[c] Innovation Agency of São Paulo State University (AUIN/UNESP), Brazil.

Abstract

Managing aquaculture systems for maximizing not only fish productivity, but also other potential benefits that the "aqua-ecosystems" can provide is a pathway towards more sustainable systems. This study aims to provide a donor-side approach for accounting the ecosystem functions and its roles on providing services and dis-services in freshwater aqua-ecosystems. We applied emergy synthesis on nine semi-intensive lambari aquaculture farms as a model to identify the connections between aquaculture practices and the ways they may increase or diminish aqua-ecosystem services. We accounted for seven water ecosystem functions that are linked to four ecosystem services and three disservices provided by lambari culture in freshwater ponds. Water regulation and microclimate regulation are services inherent to the systems features. Water provision, fish provision, and global climate regulation are influenced by the management practices adopted and can have a positive or a negative impact. In this study, the eutrophic effluent causes the larger disservice by demanding energy for water dilution (range from 4.30E+12 to 1.69E+13 sej/ha.year^{-1}) or treatment (range from 1.45E+15 to 5.65E+15 sej/ha.year^{-1}). Greenhouse absorption and emissions vary according to the management practices adopted, and in this study has a neutral effect on global climate change. The trade-offs between positive and negative externalities in lambari aquaculture indicates that the services surpasses the disservices as long as the system operates under nature's carrying capacity.

Keywords: Ecosystem approach for aquaculture; freshwater resources; ecosystem services; emergy; sustainability.

1. Introduction

Aquaculture systems are widely recognized as an alternative for the future of animal protein production, with prospects to deliver high quality food for the increasing world population (FAO, 2020). Nevertheless, the fast expansion of the activity has amplified the concern over its sustainability on the long term. While the negative impacts of aquaculture production on the natural environment and local communities had decreased over the past years, efforts remain crucial for facing the imminent threats of climate change and the post-pandemic crisis (Boyd et al., 2020). The harms caused by climate change comprise the extreme weather events, such as floods and droughts that will become more frequent and intense, consequently affecting the resilience of the aquaculture systems (Ahmed et al., 2018).

These forthcoming challenges will affect especially the small-scale farms, since they frequently lack of adequate technical and financial support (Ahmed et al., 2019). Besides, widespread unsustainable practices in these systems, related to water use efficiency and fish productivity, are major issues in climate change adaptation (Verdegem and Bosma, 2009). Freshwater earthen ponds are the most adopted system by small farms, and are likely to remain the prevailing system in developing areas (Edwards, 2015). Ponds produce over 90% of the total production in freshwater aquaculture, and contribute to sustain the livelihoods and food security of rural communities (Boyd and Davis, 2020). Therefore, strategies for maximizing human opportunities wile safeguarding the natural environment are urgent (United Nations, 2020).

Aquaculture ponds are engineered aquatic ecosystems, managed for improving the provision of food and income (Willot et al., 2019). As an interface between natural and human-made capital, it relies on both natural and economy domains for the delivery of inputs, management of production processes, and wastes recycling. This definition was previously applied in agriculture ecosystems, named as “agro-ecosystems”, but it also suits for aquaculture, named as “aqua-ecosystems” (Shah et al., 2019; Willot et al., 2019). Human interventions has intended to maximize the provisioning service of such systems, by constantly improving intensification technologies, which resulted on high productivity and efficiency (Boyd and Davis, 2020). On the other hand, these interventions have led systems to an overload on natures capacity to absorb pollution and restore natural stocks that sustain the activity itself (Ahmed et al., 2019; Bosma and Verdegem, 2011; Boyd et al., 2020).

Managing aquaculture systems for maximizing not only fish productivity, but also other potential benefits that the "aqua-ecosystems" can provide, is a pathway towards more sustainable systems (Willot et al., 2019). Ecosystem services (ES) concept defines the vast contributions that human beings obtain from the natural ecosystems for sustaining human life and wellbeing (Costanza et al., 2017). Currently, it was identified more than 40 potential ES provided by aqua-ecosystems, including provisioning, regulating and cultural services (Alleway et al., 2019; Beveridge et al., 1997; Custódio et al., 2020; Weitzman, 2019; Willot et al., 2019). While a proper management can improve ES delivery, unsustainable practices also generates dis-services, defined as the ecosystems functions and aspects that results in perceived or actual damage for human wellbeing (Costanza et al., 2017; Shah et al., 2019).

The trade-offs between positive and negative externalities are hard to evaluate, and therefore, they are rarely presented on ES valuation studies (Yang et al., 2018). Difficulties increase as one particular practice can deliver services and dis-services concurrently. For example, a shellfish farm operation at a certain area can improve water quality by filtering organic particles suspended in the water column, while at the same time causing damage to the benthonic environment by shellfish feces (Suplicy, 2020). Frameworks for evaluating ES in aquaculture systems has been a hot topic on the recent scientific literature (Alleway et al., 2019; Custódio et al., 2020; Needles et al., 2015; Weitzman, 2019; Willot et al., 2019). Nevertheless, the receiving-side approaches considered by them can be highly variable and subjective, as they rely on humans` perceptions and willingness to conserve a service or product, and do not account on the ecosystems structural and functional components (Giannetti et al., 2011). These procedures leads to over or underestimations of the material world, failing to comprehend the real wealth produced by nature (Odum and Odum, 2000; Yang et al., 2018).

Ecosystem services (ES) derive from ecosystems functions (EF), which are the ecological processes that control the fluxes of energy, nutrients and organic matter, through ecological systems (Lee and Brown, 2021). Besides, the ability of an ecosystem to provide services depends on the ability of the ecosystem to capture the natural resources available (Lu et al., 2017). Therefore, a donor-side evaluation is the most adequate approach to separate EF from ES, and to determine the efficiency of ecosystems to produce services (Lee and Brown, 2021; Lu et al., 2017). Emergy synthesis is a biophysical approach, based on a donor-side perspective valuation that recognize all the work done by nature in making available a resource (Odum, 1996). The understanding of the emergy driving flows and its configuration allows the design of higher effective policies for the global sustainability objectives.

Assessing ecosystem functions flows and its services trade-offs is fundamental for managing the aqua-ecosystems so they can sustainably provide the services humans need with the minimum damage possible. Since water is a core element for freshwater aquaculture, understanding the roles of aquatic EF in pond aquaculture is a strategic step towards sustainability (Boltz et al., 2019; Goddard and Delghandi, 2020). Moreover, it can increase aquaculture resilience for facing climate change disturbances that are water related (Ahmed et al., 2018). Therefore, this study aims to provide an emergy-based method for accounting the ecosystem functions and its roles on providing services and dis-services in aqua-ecosystems. We identified the main connections between aquaculture practices and the ways they may increase or diminish aqua-ecosystem services. Finally, we applied emergy synthesis on semi-intensive lambari aquaculture farms as a case study.

2. Materials and methods

2.1 Ecosystem services survey and emergy synthesis of ecosystem functions

Several studies have highlighted the need of a non-monetary approach for the assessment of nature's work as a complementarian valuation (Costanza et al., 2017). Emergy synthesis has shown to be the most appropriate method for assessing ecosystem functions, which are the ecological processes that sustain the delivery of ecosystem goods and services (Lee & Brown, 2021). The emergy synthesis is an eco-centric approach that accounts for all the work done by nature, society and economy on a common basis: solar-equivalent joules, named solar emjoules (sej). In other words, emergy with m, is all the available energy directly and indirectly embodied for the production of a good or service (Odum, 1996).

The ecosystem services provided by freshwater pond aquaculture were identified based on the available literature (Custódio et al., 2020; Fu et al., 2018; Willot et al., 2019). They were summarized as water regulation, water provision, global climate regulation, microclimate regulation and fish provision. A system diagram was designed for the lambari aquaculture system, aiming to identify the ecosystem functions related to the services provided. Then, the emergy flows driving each function was highlighted and further accounted. The calculation procedure was modified from Shah et al. (2019) and Yang et al. (2019), and the equations are described below.

2.2. Ecosystems functions accounting procedure

2.2.1. Groundwater recharge: The emergy driving groundwater recharge was calculated by:

$$Em_{gr} = K_i * p * G * UEV_{wi}$$

where:

Em_{gr} = Emergy used to replenish the groundwater stock (sej/ha.yr^{-1});

K_i = Seepage rate of soil *i* of the aquaculture pond (m^3/ha.yr^{-1}). For the studied system, the soil is predominantly clay type with a seepage range from 1.25 to 10 mm/day (Dias de Oliveira and Moraes, 2017; FAO, 2021);

p = Water density (g/m^3);

G = Gibbs free energy (4.49 J/g);

UEV_{wi} = Unity Emergy Value of water infiltration (2.04E+04 sej/J, Brown and Bardi, 2001).

2.2.2 *Greenhouse gases absorption/emission*: The emergy driving greenhouse gases absorption and emission was calculated by:

$$Em_{gg} = CO_{2-eq}(a-e) * G * UEV_{phyto}$$

Where:

Em_{gg}= is the emergy used for greenhouse gases absorption/emission (sej/ha.yr^{-1}). When emissions surpass absorption, the system provides a disservice. When absorptions surpass emissions, the system provides a service;

CO_{2-eq} = is the total greenhouse gases accounted in CO_2 equivalents. For the present study, the amount of greenhouse gases emitted and absorbed by the ponds was calculated according to Valenti et al., (2018);

a = is the total mass of CO_2 equivalents absorbed by the system (g/ha.yr^{-1});

e = is the total mass of CO_2 equivalents emitted (g/ha.yr^{-1});

G = Gibbs free energy (8.96E+03 J/g);

UEV*phyto* = is the Unity Emergy Value of phytoplankton productivity (1.94E+04 sej/J, from Giannetti et al., 2019).

2.2.3 Water purification: The emergy driving the water purification function in aquaculture systems was calculated under two perspectives:

A) Water dilution method: is the emergy driving the effluent dilution, which accounts for the nature's investment on recovering the resource quality by diluting the nutrients in a higher volume of water so the ecosystem can assimilate it and avoid eutrophication. The accounting procedure was:

$$Em_{wd} = \left(\frac{N_{out}}{N_{st}} * EV\right) * p * G * UEVsw$$

Where:

Em_{wd} = is the emergy driving the dilution process (sej/ha.yr^{-1});

N_{out} = is the nutrient (phosphorous or nitrogen) concentration in the effluent water (mg/l);

N_{st} = is the standard or targeted concentration of the same nutrient on a high quality water, or the nutrient concentration in the inlet water used by the farm (mg/l). In the present study, we adopted the standard concentration of phosphorous for class 1 freshwater, defined by the Brazilian Environmental Council, which is 0.02 mg/l (CONAMA, 2005);

EV = Is the volume of the effluent discharged by the aquaculture ponds (l/ha.yr^{-1})

p = Water density (g/l);

G = Gibbs free energy (4.49 J/g);

UEV_{sw} = is the Unity Emergy Value of superficial water (5.23E+04 sej/J, from Comar, 2001).

B) Water treatment method: the emergy driving the construction and maintenance of a water treatment plant, which accounts for the nature's investment in a system that replaces the natural purification service. It was calculated by:

$$Em_{wt} = \sum (R * UEV_R) + (N * UEV_N) + (F * \ UEV_F)$$

Where:

Em_{wt} = is the emergy driving a wetland system for water treatment (sej/ha.yr^{-1});

R = is the total amount of renewable resources used, such as sun, wind and rain (joules, g or US$ /ha.yr^{-1});

UEV_R = is the Unity Emergy Value for each renewable input (sej/unity);

N = is the total amount of local non-renewable resources used, for example soil (joules, g or US$ / ha.yr^{-1});

UEV_N = is the Unity Emergy Value for each non-renewable input (sej/unity);

F = is the total amount of consumed resources from economy, such as materials, fuels, electricity and money (joules, g or US$ / ha.yr^{-1});

UEV_F = is the Unity Emergy Value for each "F" resource (sej/unity).

2.2.4 Evaporation: The emergy of water evaporation was calculated by:

$$Em_{we} = E_i * p * G * UEV_{we}$$

Where:

Em_{we} = is the emergy driving water evaporation (sej/ha.yr^{-1})

Ei = is the annual evaporation (m³/ ha.yr^{-1}). In the present study, we adopted the average evaporation rate for freshwater ponds (range from 1.0 to 2.3 m³/ha.yr^{-1} for tropical ponds, from Verdegem et al., 2006);

p = Water density (g/m³);

G = Gibbs free energy (4.49 J/g);

UEV_{we} = is the Unity Emergy Value of water evaporation (7.23E+03 sej/J, from Giannetti et al., 2019).

2.2.5 Biomass increase: The emergy driving biomass increase in aquaculture systems is the same of the emery driving the aquaculture farm. It includes all the resources that are needed for increasing productivity, such as electricity, fuel, labor and others. It was calculated by:

$$Em_{bm} = \sum (R * UEV_R) + (N * UEV_N) + (F * UEV_F)$$

Where:

Em_{bm} = is the emergy driving biomass increase in an aquaculture system (sej/ha.yr^{-1});

R = is the total amount of renewable resources used, such as sun, wind and rain (joules, kg or US$ /ha.yr^{-1});

UEV_R = is the Unity Emergy Value for each renewable input (sej/unity)

N = is the total amount of local non-renewable resources used, for example groundwater (joules, kg or US$ / ha.yr^{-1});

UEV_N = is the Unity Emergy Value for each non-renewable input (sej/unity)

F = is the total amount of consumed resources from economy, such as materials, fuels, electricity and money (joules, kg or US$ / ha.yr^{-1});

UEV_F = is the Unity Emergy Value for each "F" resource (sej/unity).

Details on the emergy accounting of lambari systems can be found in chapter 1.

2.3 Case study: data source and results analysis

We applied the previous described procedure on nine semi-intensive lambari aquaculture farms. The farms produce the yellowtail lambari (*Astyanax lacustris*) in semi-intensive earthen ponds, intensively fed with commercial feed. Lambari farms differ for land and pond sizes, management strategies, and capital for economic investments in infrastructure and equipment. These dissimilarities resulted in the three categories, or levels of control, according to systems technification degree: low control, moderate control, and high control. The details on the practices of the control levels can be found at chapter 1. Data on natural and economic inputs, management practices and landscape features were obtained in situ. Additional information were obtained through a semi-structured survey applied to the nine farmers in the beginning of the production cycle. The questionnaire focused on accounting for the total amount of materials, equipment, and infrastructure purchased, as well as labor, taxes, and depreciation. All inflows of materials, energy and money were accounted in unities/hectare, and they correspond to one year (i.e. 3 production cycles) of farm operation. The equations for the ecosystem functions evaluation were applied to each ecosystem function, in each lambari farm, separately.

3 Results

The ecosystem services and disservices provided by the freshwater pond aquaculture rely on the ecological functions that are linked with the production system (Figure 1). The functions of groundwater recharge and evaporation are inherent to the system, and occur independently of human interventions. The greenhouse gases balance depends mainly on the primary productivity potential and bottom soil quality, which are influenced by the management practices of the system. The water purification process is linked to the water source input, the amount of allochthone nutrients inputs, and the management practices, as they determine the quality of the outlet water. The interaction of these flows may cause an energy depreciation, by the natural effort on deviating energy for reestablishing the water quality. All ecosystem functions identified have a regional influence, except for greenhouse gases that have a global influence.

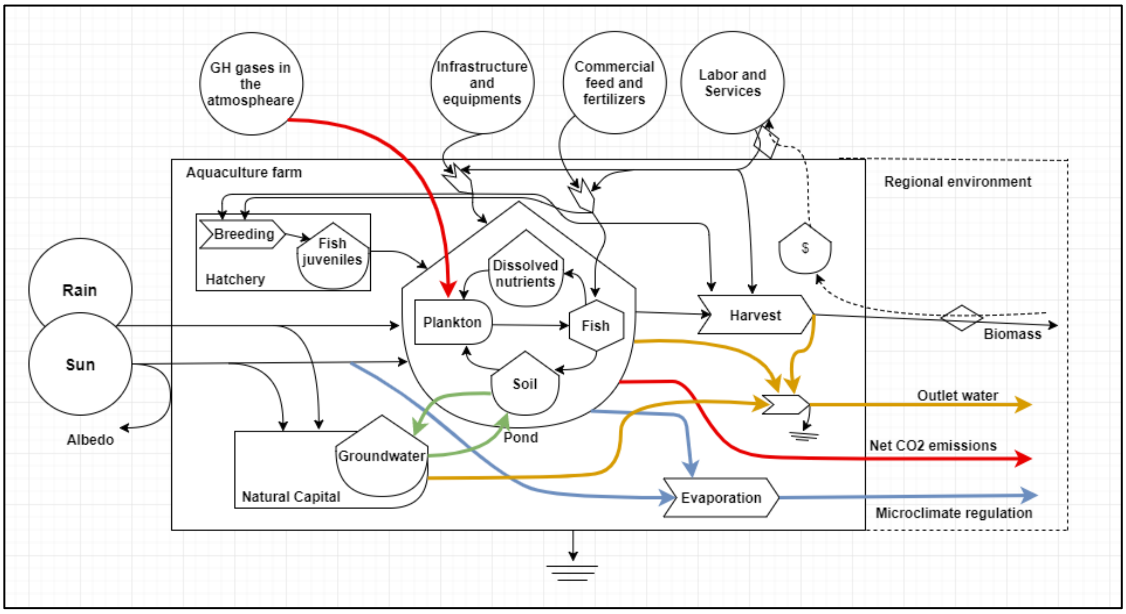

Figure 1 - Energy system diagram of a lambari freshwater pond aquaculture system. Circles represent emergy natural and economy sources, arrows represent flows of emergy that interact with the internal stocks for producing the goods and services. Red arrows are the emergy flows driving greenhouse gases absorption and emissions. Green arrows are the emergy flows driving groundwater recharge. Blue arrows are the emegy flows driving evaporation. Yellow arrows are the emergy flows driving water purification. Black arrows are the emergy flows driving biomass increase. For details on the symbols of energy systems diagrams see Odum (1996).

The main services provided by the lambari aquaculture ponds are water regulation, microclimate regulation and fish provision (Table 1). These services depend on the functions of groundwater recharge, evaporation and biomass increase. Biomass increase is the main goal of this aqua-ecosystem, and therefore, demands a high emergy amount that varies according to the systems efficiency. Water purification, which in this case is water pollution, is the largest ecosystem disservice of lambari pond systems, in both ecosystem functions assessed, but the emergy driving water treatment is larger than the emergy driving effluent dilution. Global climate regulation service and disservice are highly variable between the farms assessed, and can be considered as neutral since the emergy driving emissions are similar to the emergy driving absorption. The trade-offs concerning the flows of emergy driving services and disservices have a positive result even when the biomass increase is not accounted.

Table 1 - Emergy flows driving the water ecosystem functions that support the delivery of ecosystem services and disservices in lambari freshwater pond aquaculture systems. Flows are accounted in sej (solar emjoules) per hectare per year. Positive values are services and negative values are disservices. Net emergy = emergy flow of services – emergy flow of disservices.

Ecosystem service	**Ecosystem function**	**Type**	**Emergy flow (sej/ha.yr^{-1})**	
			Min	**Max**
Water regulation	Groundwater recharge	Service	4.18E+14	3.34E+15
Water purification	Water dilution	Disservice	- 4.30E+12	- 1.69E+13
Water purification	Water treatment	Disservice	- 1.45E+15	- 5.65E+15
Global climate regulation	Greenhouse gas uptake	Service	7.39E+15	1.43E+17
Global climate regulation	Greenhouse gas release	Disservice	- 5.36E+15	- 1.29E+17
Microclimate regulation	Evaporation	Service	3.25E+10	7.47E+10
Fish provision	Biomass accumulation	Service	6.23E+16*	1.07E+18*
Total emergy flow driving services, excluding biomass accumulation			**7.81E+15**	**1.46E+17**
Total emergy flow driving disservices, considering water dilution			**5.37E+15**	**1.29E+17**
Total emergy flow driving disservices, considering water treatment			**6.81E+15**	**1.34E+17**

* Biomass accumulation in sej/ha.yr^{-1}, excluding services (i. e. the monetary flow).

4 Discussion

Aquaculture ponds are aqua-ecosystems that provides services and disservices. In the present study, we identified and assessed seven water ecosystem functions that are linked to four ecosystem services, and three disservices provided by lambari culture in freshwater ponds. Water regulation and microclimate regulation services are inherent to the systems features, while water purification, fish provision, and global climate regulation, are influenced by the management practices adopted, and can have positive or negative impact. In this study, the eutrophic effluent causes the larger disservice by demanding energy for water dilution or treatment. Greenhouse absorption and emissions vary according to the management practices, and in this study has a neutral effect. Overall, the services provided by the aqua-ecosystem surpass the disservices under an eco-centric point of view, as long as the system operates under the carrying capacity of the watershed.

Water seepage is an inherent feature of aquaculture earthen ponds, and often represent a technical and environmental problem as it increases the water inflow needed for maintaining the pond level (Bosma and Verdegem, 2011; Boyd and Davis, 2020). Nevertheless, the water that infiltrates through the lateral and bottom soil of ponds, reaches the water table. The soil and underlying geological formations act as a filter for organic pollutants and harmful bacteria that may be present, restoring water quality (Boyd et al., 2002). The ponds temporally retains water from rain and streams, but a fraction of that water potentially recharge the groundwater stocks. By doing so, aquifers may stock high quality water that are essential for maintaining water cycle and securing water availability. This result indicates that pond aquaculture could be an economic activity introduced in degraded areas, such as eroded lands, as a strategy for recovering the natural capital of the area while benefiting people.

Water evaporation occurs directly from pond surfaces, and is controlled by water and air temperature, humidity, wind velocity, and atmospheric pressure (Boyd and Davis, 2020). Water evaporation from aquatic environments plays an important role on the air quality and thermal comfort, especially in areas suffering with intense and long drought season (Yang et al., 2019). Besides, the service of microclimate regulation is becoming more relevant as climate change intensifies the drought periods. The lambari aquaculture farms studied are located in the southwest region of São Paulo state in Brazil. That landscape area is characterized by the predominance of sugarcane monocultures, which has a high negative impact on the regional air quality due to emissions caused by inadequate harvest practices (Bordonal et al., 2018). Therefore, the Integration of sugarcane and livestock sectors such as aquaculture is recommended to improve land use efficiency in Brazil, since it would increase productivity while mitigating the negative impacts of highly intensive monocultures (Bordonal et al., 2018).

Water purification in aquatic ecosystems is their capacity to remove contaminants by dilution, sedimentation, aeration, absorption, flotation, chemical and biological reactions (Yang et al., 2019). The biophysical mechanisms of aquaculture ponds are similar to any lotic environment (Boyd and Davis, 2020). Nevertheless, human interventions on aquaculture ponds aims to overpass its natural productivity by adding alloctonous sources of energy and nutrients. Normally, only 20-40% of the nitrogen and phosphorous added by fertilization and feed to a pond is recovered on fish biomass (Bosma and Verdegem, 2011). From what remains, it becomes effluents to be discharged mainly in the local streams (Boyd and Davis, 2020; Verdegem and Bosma, 2009). Because of the eutrophic nature of aquaculture effluents, as in the case of lambari farms, it can have a negative additive effect on the receiving waterbody, spread disease, and decrease the quality of water downstream (Verdegem and Bosma, 2009).

When the farms externalize these negative impacts, natures deviates energy from other ecological processes for reestablishing the resource quality. The environmental cost of recovering water quality is lower when the dilution of the effluent by the receiving water body is possible. Nevertheless, the carrying capacity of the watershed has to be considered. In the present study, each m^3 of effluent costs in average 17 m^3 of high quality water invested by nature. On the other hand, the water treatment by a simple wetland plant consumes 200 times more emergy per hectare of farm. As an alternative, aquaculture systems could make use of hypereutrophic water sources for maximizing the use of nutrients, which results on a higher quality outlet water compared to its source (David et al., 2017; Flickinger et al., 2019). Moreover, the Integrated multi-trophic aquaculture (IMTA), as well as non-fed species culture has ecosystem functions that purify the water used(Alleway et al., 2019; Custódio et al., 2020; Franchini et al., 2020). These innovative approaches may be an alternative for internalizing this disservice caused by lambari aquaculture effluent.

Aquaculture emits and absorbs carbon concomitantly (Ahmed and Thompson, 2019; Boyd and Davis, 2020). Carbon emission occurs via bubbles released from the sediment during the process of organic matter decomposition (Valenti et al., 2018). Additionally, exchanges of gas between the water surface and the atmosphere releases the CO2 produced by then respiration process of water animals, plants and microbiota (Valenti et al., 2018). On the other hand, the photosynthesis mechanism relies on carbon sequestration during the daytime (Bosma and Verdegem, 2011). Therefore, the balance of emitted versus absorbed carbon of an aquaculture system demonstrates the contribution of the systems as a service or di-service provider. The emergy valuation suggested that lambari aquaculture has a neutral effect on global climate regulation; nevertheless, the results are highly variable among farms, indicating that location, pond age, feed management and species cultured may affect the carbon balance (Flickinger et al., 2020).

The trade-offs between positive and negative externalities in lambari aquaculture indicates that the services surpasses the disservices as long as the system operates under nature's carrying capacity. Moreover, systems must be designed considering the internalization of the externalities, aiming to maximize the positive and minimize the negative. Nevertheless, the internalization of the environmental costs by remediating the damage does not necessarily leads to more sustainable systems. By doing so, more energy and resources are needed, which diminishes the natural capital in detriment of recovering the damage caused by the system itself. An ecological approach that considers the integration of species and cultures, the upcycling of resources, and the surrounding biophysical aspects, makes systems higher efficient at a lower environmental cost, which seems much more effective on the long term.

The ecosystem features and their ability for converting the available resources into services are determinant for the quantity and quality of services delivered. Lee & Brown (2021) stated that the value of an ecosystem function is the total emergy driving the system, and since the functions are co-products of an ecosystem driven by the same sources, they should not be added. Moreover, a static evaluation does not account for the feedback and cycling of emergy over time scales greater than one year (Lee & Brown 2021). Nevertheless, when assessing EFs in a production system that is artificially organized for maximizing productivity regardless of other possible environmental services and disservices, the valuation of the emergy flows driving the specific EFs can be strategic for sustainability. An environmental management of human-made ecosystems that maximizes the emergy production and use is more likely to enhance the delivery of goods and services (Odum e Odum, 2000).

5. Conclusion

Besides fish provision, aquaculture freshwater pond systems provides ecosystem services and disservices that rely on the ecological functions of the system. The services of water regulation and microclimate regulation are positive inherent features of the system, and rely on groundwater recharge and evaporation functions. Greenhouse absorption and emissions vary according to the management practices applied, and in this study has shown a neutral effect on global climate regulation. The eutrophic quality of the farms effluent causes the higher disservice, by wasting resources for recovering the water quality. The trade-offs between positive and negative externalities in lambari aquaculture indicates that the services surpasses the disservices as long as the system operates under nature's carrying capacity. An ecological approach that considers the integration of species and cultures, the upcycling of resources, is more effective in the internalization of the positive and negative externalities, improving systems sustainability and resilience by restoring the natural capital.

Acknowledgements

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CAPÍTULO 3: Multi-Criteria Sustainability Assessment of Lambari Aquaculture in Brazil

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Multi-Criteria Sustainability Assessment of Lambari Aquaculture in Brazil

Tamara Fonseca[a2], Wagner C. Valenti[a,b], Biagio F. Giannetti[c], Fernando H. Gonçalves[a], Feni Agostinho[c]

[a] Aquaculture Center, São Paulo State University (UNESP). Road Paulo Donato Castellane, Jaboticabal -SP, zip code 14884-900, Brazil.
[b] Innovation Agency of São Paulo State University (AUIN/UNESP): Reitoria da UNESP, Quirino de Andrade Street 215, zip code: 01049-010 - São Paulo - SP – Brazil.
[c] Post-graduation Program on Production Engineering, Paulista University (UNIP). Luís Góis Street 2211, zip code: 04043-200, São Paulo – SP – Brazil.

Abstract

Lambari aquaculture has the opportunity to promote sustainable development for rural populations. For that, efforts on the assessment, monitoring and planning of sustainability are a mandatory pathway. This study applies the five sector multi-criteria sustainability assessment (5SEnSU) on lambari aquaculture farms, as a model for investigating the sustainability of small-scale freshwater aquaculture in Brazil. We studied nine aquaculture farms, located in southeast region. Indicators of environmental, social and economic sustainability were selected according to the 5SEnSU model and analyzed by goal programming. The aquaculture systems studied have different performances of sustainability, depending on the level of control of major farming variables. Low control farms performed better at the social dimension, contributing mainly for the local socio-economic development and for the maintenance of rural livelihoods. On the other hand, moderate and high control farms performed better at the environmental and economic dimensions as they use natural resources more efficiently and achieve higher productivity and profitability. Results indicated that a systemic and multi-criteria approach can be useful for the strategic planning towards the sustainable development of smallholder aquaculture systems.

Keywords: smallholder aquaculture; sustainable development; indicators; multi-criteria assessment.

[2] Corresponding author: MSc. Tamara Fonseca, São Paulo State University (UNESP), Aquaculture Center, Road Paulo Donato Castellane, Jaboticabal, Zip code 14884-900, São Paulo, Brazil, Phone +55 11 984876352. Email address: tamara.fonseca@unesp.br, ta.fonseca@hotmail.com.

1. Introduction

Aquaculture is the fastest growing food production sector in the recent decades, and is expected to grow 37% by 2030 (Garlock et al., 2020). The world aquaculture production reached 82.1 million tonnes of fish and 32.4 million tonnes of aquatic plants in 2018, and has already surpassed the wild catch in 35 countries (FAO, 2020). Brazil has exceptional environmental and social conditions to produce aquatic organisms, and currently occupies the 8th position in the world ranking of the largest producers of fish by aquaculture. In 2019, the production was ~800,000 tonnes, which represents a gross revenue of about US$ 1 billion, mostly commercialized at the domestic market (IBGE, 2020; Valenti et al., 2021). The freshwater fish species are the most produced, and the culture of native species is widespread in Brazil, playing a very important role on socioeconomic development. Most of the Brazilian aquaculture production comes from small rural properties (<2 ha), where the production is carried out mainly in freshwater ponds (95%). Currently, more than 200 thousand freshwater fish farms are active in Brazil (Valenti et al., 2021).

The global major challenges for the freshwater aquaculture are currently related to government regulation, the lack of a structured production chain, environmental pollution, the scape of alien and interspecific hybrid species, animal welfare and health, adequate nutrition and technical support (Boyd et al., 2020; Brugère et al., 2019; Henares et al., 2019). The scientific community has developed several technologies for addressing some of these challenges. Among others examples are: technology for effluents treatment, native species breeding and rearing methods, suitable drugs and probiotics, genetic improvements, decrease of the feed conversion ratio, replacement of fish meal in aquafeed by vegetal protein, and recirculating systems (Antonucci and Costa, 2020; Dawood et al., 2019; Humphries et al., 2019; Lulijwa et al., 2019; Tacon, 2020). Despite the significant improvements achieved, solutions are costly and frequently unattainable by small farmers. Moreover, current technology could prove ineffective at mitigating the complex threats caused by SARS-CoV-2 and climate change crises in the near future. Therefore, innovative technologies that can adjust to all these challenges will be vital for its sustainability in the long term.

Sustainability is a fundamental goal for the development of human society, and has been a major concern for the future of aquaculture (Boyd et al., 2020; FAO, 2020; United Nations, 2015). The recent discussions on the topic have focused on assessing the sustainability of different production systems, management practices and levels of intensification. For this, several assessment methods have been used, such as life cycle assessment (LCA), set of sustainability indicators and emergy synthesis (David et al., 2020; Mungkung et al., 2013; Valenti et al., 2018). Nevertheless, small rural producers, who represent the majority of systems in operation in Brazil, have received little attention in strategic planning for the sustainable development of the activity worldwide (Brugère et al., 2019). Even though research had investigated the role of rural aquaculture systems on poverty reduction (Béné et al., 2016), the analysis lack of a systemic approach to investigate the systems' functioning and the ways they relate to the social, economic and environmental spheres in which they are inserted.

Lambari (*Astyanax lacustris*) is a freshwater small native fish cultured for the market of live bait for sport fishing (Fonseca et al., 2017). The production is concentrated in the southern and southeastern region, mainly in São Paulo State. The current production is estimated to be above 1,000 tonnes per year, which most part is commercialized alive at the farm gate, although the market for human consumption and a dedicated processing plant exist in Brazil (Valenti et al., 2021). The bulk of production comes from small ponds (0.03 to 0.03 ha), in small farms, where the fish is cultured in fed monoculture systems although a commercial feed designed for the nutritional requirements of the specie is inexistent. Moreover, the activity faces the same challenges as the majority of small rural aquaculture systems in Brazil: poor management practices, lack of a structured production chain, adequate nutrition, environmental pollution and technical support (Valenti et al., 2021). Nevertheless, as a native low-trophic specie, lambari aquaculture has the opportunity to promote sustainable development for rural populations (Fonseca et al., 2017). For that, efforts on the assessment, monitoring and planning of sustainability are a mandatory pathway. Therefore, lambari aquaculture systems are a good model for the study of the sustainability of small freshwater pond aquaculture, since their prospects and challenges are similar to the overall small aquaculture farms worldwide.

The multicriteria assessment of sustainability based on the five sectors (model 5SEnSU) can be a useful tool for measuring and establishing goals for the sustainable development of aquaculture in Brazil. The model is based on the premise that human systems are thermodynamically open, which demands energy and materials from nature that will be transformed into goods and services by means of human work (Bastianoni et al., 2016; Giannetti et al., 2019b). According to the conceptual model of 5SEnSU, the environment acts as a supplier of natural resources (sector 1) and as a receiver of by-products and wastes (sector 2) from the productive sector (sector 3). On the other hand, society acts as a supplier of labor and technology (sector 4), and as a receiver of goods and services (sector 5) produced by sector 3 (Giannetti et al., 2019b). This model allows a holistic view of the production system, which occurs through the quantification of physical exchanges that occur between the environmental, economic and social sectors, which provides a scientifically robust measurement of the sustainability of the production systems. Therefore, this study applies the 5SEnSU multi-criteria assessment on lambari aquaculture farms as a model for investigating the sustainability of small-scale freshwater aquaculture in Brazil.

2. Materials and Methods

2.1 - *Farms description and data source*

We studied nine aquaculture farms that produce the yellowtail lambari (*Astyanax lacustris*) in intensively fed monoculture using earthen ponds. The farms differ by land and pond sizes, management strategies, capital for economic investments in infrastructure and equipment, technification, and control of the system by the operators. These dissimilarities resulted in the three categories, or levels of control: low control, moderate control, and high control. The details on the practices of the control levels can be found at chapter 1. Data on natural and economic inputs, management practices and landscape features were obtained in situ through a semi-structured survey applied to the nine farmers. The questionnaire focused on accounting for the total amount of materials, equipment, and infrastructure purchased, as well as labor, taxes, and depreciation. Additional information was obtained on the available literature. All inflows of materials, energy and money were accounted in unities/hectare, and they correspond to one year (i.e. 3 production cycles) of farm operation.

2.2 – Five sector sustainability (*5SEnSU) conceptual model*

Human-driven systems are biophysically open systems, which demand energy and materials inputs that are transformed by means of human labor efforts into goods, services and wastes (Bastianoni et al., 2016). Assuming that, the 5SEnSU model considers the social, economic and environmental dimensions of sustainability, based on their functions and on the biophysical exchanges among them (Figure 1). According to the model, the environment dimension act as a provider of raw materials and energy (Sector 1), and as a receiver of wastes and emissions (Sector 2) from the production system (Sector 3). On the other hand, society acts as a provider of human capital (Sector 4), and as a receiver of the products or services and externalities (Sector 5). The first step of the 5SEnSU assessment is the selection of indicators. In the present study, two indicators were selected for each of the five sectors of the model, allowing a balance among the environmental, social, and economic dimensions of sustainability (Giannetti et al., 2019b). They were selected according to their relevance, sensitivity, and representativeness of the sector, and account for a time-window of one year of farm operation.

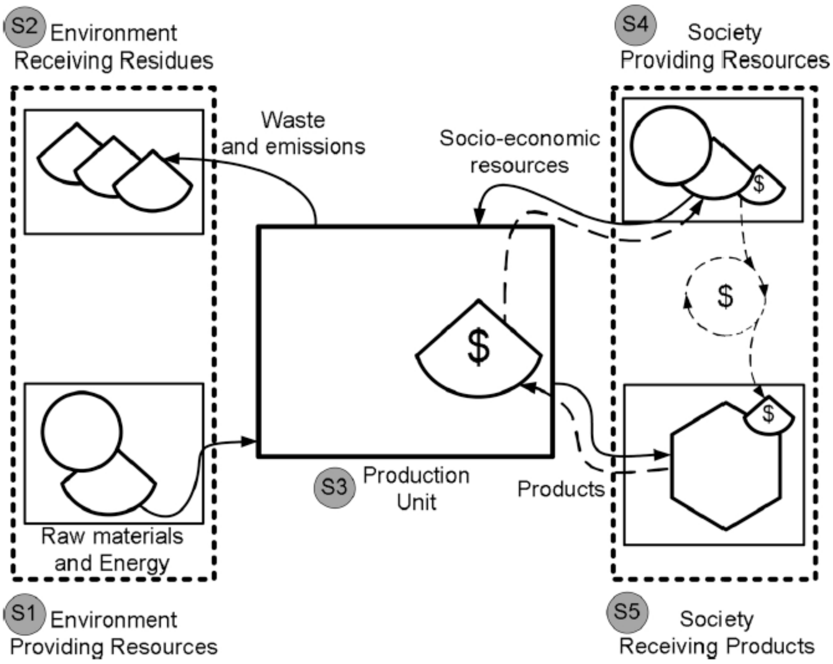

Figure 2- FIVE SEctor SUstainability (5SEnSU) model from Giannetti et. al. (2019). The symbology used here comes from the emergy accounting method as available in Odum (1996), where circles mean energy sources, "water tank" means storage, hexagon means consumers, continuous arrows mean material and energy flows and dashed arrows mean money flows. S=sector.

For the sector 1, Unity Emergy Value (UEV - sej/kg) and use of water (m^3/kg) were selected as indicators of the efficiency of the aquaculture system for converting natural resources into fish (UEV), and of the systems' reliance upon the water resources. For the sector 2, the flow of positive and negative ecosystem functions (sej/ha/year) were selected as indicators of the roles of the aquaculture system on restoring and depleting the functioning of the ecosystem in which the system is inserted. Productivity (t/ha) and Internal Rate of Return (%) were the indicators selected to demonstrate the economic performance of the sector 3. For the sector 4, the local jobs generation (%) and the time of permanence of the farmers at the business (years) are indicators of the contribution of the local community to the enterprise. For the sector 5, the fraction of the lambari production that is consumed locally (%), and the fraction of inputs for production that is purchased locally (%) are the indicators of the benefits received by the local community.

2.3 - *Multi Criteria Decision Making: goal programming*

The sustainability assessment of the 5SEnSU model was based on the goal programming method for the multi criteria decision making (Giannetti et al., 2019b). This approach allows handling multiple, normally conflicting goals represented by indicators. In summary, the logic is to measure the distance of the assessed system, represented by an indicator, from achieving the desired goal. The deviation can be either positive or negative, depending on the objective of maximizing or minimizing the chosen indicator. In the present study, no weigh was assigned as the sectors were assumed to have equal relevance. The goals established were the maximum value found among systems for the objective of maximizing, and the minimum value for the objective of minimizing. The equations of the GP procedure are as follows:

(1) $ISG^{+}_{ijk} - \sum_{ijk} \frac{N^{+}_{ijk}}{W^{+}_{jk}, G^{+}_{jk}} + \sum_{ijk} \frac{P^{+}_{ijk}}{W^{-}_{jk}, G^{+}_{jk}}$

$\forall\, i \in \{1, 2, \dots NE\}\ \forall\, j \in \{1, 2, \dots NS\}\ \forall\, k \in \{1, 2, \dots NI\}$

(2) $ISG^{-}_{ijk} - \sum_{ijk} \frac{N^{-}_{ijk}}{W^{-}_{jk}, G^{-}_{jk}} + \sum_{ijk} \frac{P^{-}_{ijk}}{W^{+}_{jk}, G^{-}_{jk}}$

$\forall\, i \in \{1, 2, \dots NE\}\ \forall\, j \in \{1, 2, \dots NS\}\ \forall\, k \in \{1, 2, \dots NI\}$

ISG= index of sustainability goal of indicator

Nijk+ and Nijk− = positive and negative indicators for the negative deviation variables, respectively;

Pijk+ and Pijk− =positive and negative indicators for the positive deviation variables, respectively;

Gjk+ and Gjk− = goals for the positive or negative indicators;

Wjk+ and Wjk− = the weight for each indicator;

NE, NS, and NI are the amount of evaluated systems, sectors, and indicators per sector, respectively;

i, j, and k represents the system being evaluated, the correspondent sector to the 5SEnSU model, and the indicator(s) for each sector, respectively.

When added, the ISGs (Eqs. (1) and (2)) provide the sector sustainability indicator (SSI), representing the sum of the differences between the positive and negative deviations for each sector of 5SEnSU model:

(3) $SSI_{ij} - WS \sum_{ijk}(ISG^{+}_{ijk} - ISG^{-}_{ijk})$

$\forall\, i \in \{1, 2, \ldots NE\}\ \forall\, j \in \{1, 2, \ldots NS\}\ \forall\, k \in \{1, 2, \ldots NI\}$

in which:
WS = the weight established for each sector.

Finally, the sustainability synthetic indicator of system (SSIS) can be obtained by adding the SSI of each sector:

(4) $SSIS_{i} - \sum_{j}^{5} SSI_{ij}$

$\forall\, i \in \{1, 2, \ldots NE\}\ \forall\, j \in \{1, 2, \ldots NS\}$

3. Results

The indicators of environmental, social and economic sustainability for the nine lambari aquaculture farms are presented at table 1. Unity emergy value (UEV) and use of water were the indicators of sector 1. For UEV, the lower value indicated higher efficiency; therefore, the UEV achieved by HC2 was selected as a goal. For water use, HC1 had the lowest use of water, which was selected as a goal. In the sector 2, the values of positive ecosystem services were slightly different among the systems assessed, but the highest value were achieved by HC1. For the negative ecosystem functions, LC1 had the lowest value, which was selected as the goal. For the sector 3, HC1 and HC2, had the best performance for productivity and I.R.R. respectively. In the sector 4, the systems had equal performance for the local jobs indicator, and the HC2 had the highest value for time of permanence. Finally, LC1, LC2 and LC3 had the highest value for local consumption and for local purchases.

Table 2- Indicators of environmental, social and economic sustainability for the nine lambari aquaculture farms. UEV = Unity Emergy Value; LC= low control farm; MC = moderate control farm; HC = high control farm. Numbers represent different farms within the same control level.

	Sector 1 – Environment as a provider		**Sector 2 – Environment as a receiver**		**Sector 3 – Production system**		**Sector 4 – Society as a provider**		**Sector 5 – Society as a receiver**	
Systems	UEV (sej/j)	Water use (m³/kg)	Positive ecosystem functions (sej/ha)	Negative ecosystem functions (sej/ha)	Productivity (t/ha)	Internal Rate of Return* (%)	Local jobs generation ratio (%)	Farmer permanence on the activity (years)	Fraction of production consumed locally (%)	Fraction of inputs purchased locally (%)
LC1	2.84E+06	36,330	1.88E+15	4.30E+12	1.4	29	100	15	100	60
LC2	1.89E+06	29,273	1.88E+15	6.67E+12	3.0	20	100	25	100	60
LC3	3.07E+06	36.910	1.88E+15	9.36E+12	1.0	4	100	26	100	60
MC1	1.55E+06	6.622	1.88E+15	9.77E+12	7.7	37	100	11	75	50
MC2	9.11E+05	7.107	1.88E+15	1.69E+13	7.5	19	100	12	70	60
MC3	2.17E+06	16.843	1.88E+15	6.91E+12	3.1	18	100	5	65	50
HC1	4.68E+06	3.758	1.88E+15	1.33E+13	12.0	13	100	11	100	43
HC2	8.64E+05	13.702	1.88E+15	1.09E+13	4.0	62	100	29	10	43
HC3	2.47E+06	8.671	1.88E+15	9.88E+12	4.8	11	100	15	30	43
Objective	Minimize	Minimize	Maximize	Minimize	Maximize	Maximize	Maximize	Maximize	Maximize	Maximize
Goal	Lowest value	Lowest value	Highest value	Lowest value	Highest value	Highest value	Highest value	Highest value	Highest value	Highest value

*Annual discount rate of 12%.

According to the goal programming analysis, the system with the best sustainability performance is MC1, followed by MC2, HC2, HC3, HC1, MC3, LC2, LC1 and LC3 (Figure 2). Overall, the low control systems performed poorer at Sector 1 and Sector 3, but had a better performance at the sector 5. The MC2 and HC2 had the worst performance at sector 2. The HC2 had the best performance at sector 4, followed by LC3 and LC2.

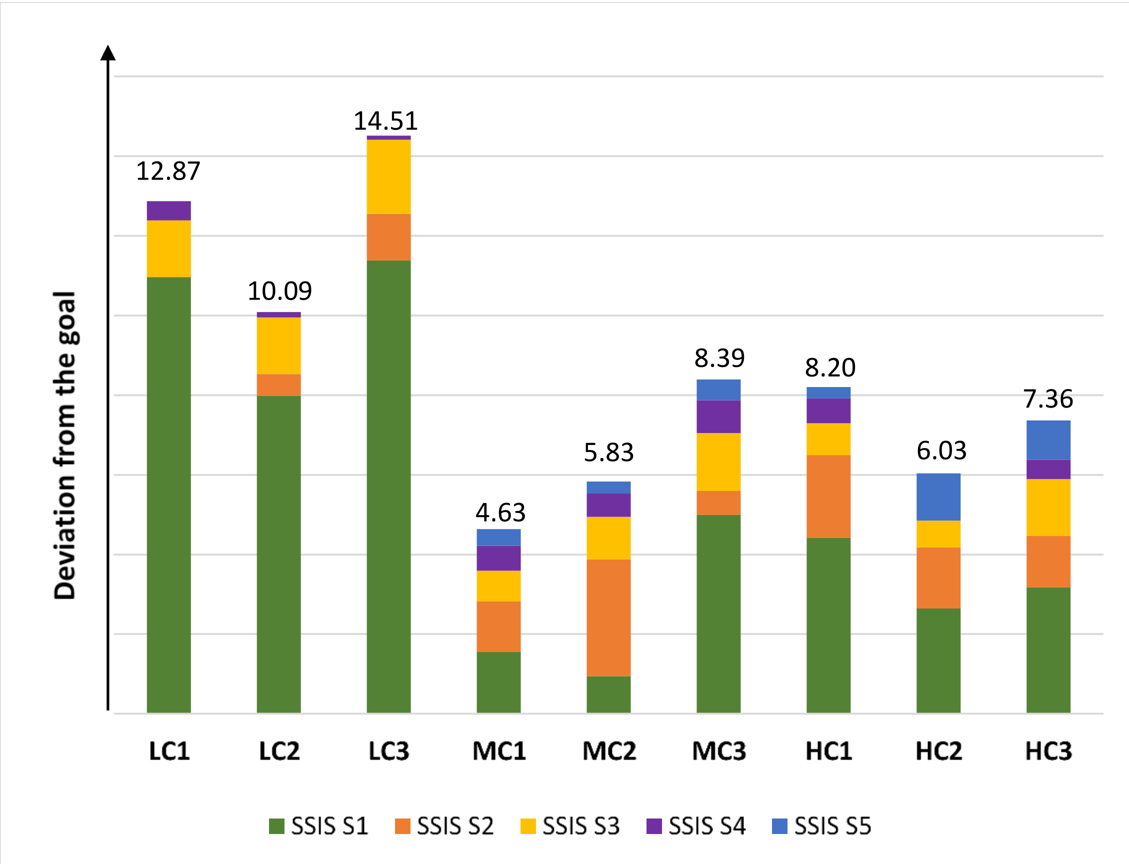

Figure 3 – Goal programming analysis accounting for the distance of each lambari farm studied from the goals established at each sector of the Five Sector Sustainability model (5SEnSU). Higher values indicate higher distance from the goal and lower sustainability. LC= low control farm; MC = moderate control farm; HC = high control farm; numbers 1, 2 and 3 represent different farms within the same control level. Numbers over the bars represent the Sustainability Synthetic Indicator of Systems (SSIS); SSIS S1 = Sustainability Synthetic Indicator of System 1; SSIS S2 = Sustainability Synthetic Indicator of System 2; SSIS S3 = Sustainability Synthetic Indicator of System 3; SSIS S4 = Sustainability Synthetic Indicator of System 4; SSIS S5 = Sustainability Synthetic Indicator of System 5. .

4. Discussion

The multi-criteria assessment of the sustainability of lambari aquaculture indicates that the lower control systems are less sustainable compared to the moderate and high control systems, which the MC1 achieved the highest sustainability. These systems had a poorer performance at sector 1, which is demonstrated by the larger deviation of the obtained indicators from the chosen goal. On the other hand, the deviation was lower for the sector 2. The LC systems also had a large deviation from the goals of system 3, which evidences the poorer performance of the system on the economic sphere. Nevertheless, the LC systems had a better performance in the sectors 4 and 5, which indicates a higher level of sustainability on the social sphere compared to the higher control systems.

The sector 1 represents the natural environment as a provider of resources for the production system (Giannetti et al., 2019b). The indicator Unity Emergy Value (UEV) accounts the systems efficiency on converting natural resources into products, in which the lower the UEV, the higher the efficiency (Giannetti et al., 2019a; Odum, 1996). The second indicator selected was water use (m^3/kg), which evidences the systems' dependence on the water resources, in which the higher the value, the lower the sustainability (Boyd et al., 2007; Valenti et al., 2018). Freshwater is a core natural resource for rural aquaculture systems, that has been threatened by irrational consumption, pollution and climate change (Ahmed et al., 2018; Goddard and Delghandi, 2020). The LC systems are low efficient in the use of water and other natural resources, which could be a result of poorer management practices of production. As demonstrated in Chapter 1, these systems lack of technical assistance on simple management practices that greatly influences their sustainability, such as the replacement of groundwater by superficial sources and a proper feeding regime. The absence of technology transfer policies that matches producers' realities is one of the greatest bottlenecks for the sustainable development of the activity in Brazil (Henares et al., 2019; Valenti et al., 2021). Therefore, extension programs devoted for smallholder farms are urgent, and should focus on low-cost alternative practices that could benefit farmers on the long term.

The environment represented by sector 2 act as a receiver of the pollution that may be generated by the production activity (Giannetti et al., 2019b). The discard of wastes compromises the natural functioning of the environment, demanding energy and resources for its recovery, which results in the depletion of natural stocks and, sometimes, the collapse of the ecosystem (Almeida et al., 2010; Bastianoni et al., 2016). On the other hand, the production system may interact in a positive way with the surrounding environment, by improving ecosystems functions that restore natural stocks (Coscieme et al., 2013; Willot et al., 2019). The lambari pond systems interact in both ways with the adjacent ecosystem (see Chapter 2). The positive functions generate services such as water regulation and microclimate regulation, which are inherent of pond systems and thus have a low variation among farms. The negative functions are caused mainly by the discard of eutrophic effluents in the watershed. This disservice is higher at moderate and high-control farms, which were demonstrated by their larger deviation from the goal at sector 2 (figure 2).

The indicators of the sector 3 demonstrate the economic performance of the lambari farm systems. The low control systems are less productive compared to MC and HC systems, which may be a result of the poorer management practices, but also the lower quantity and quality of inputs, such as commercial feed. Contrariwise, the I.R.R., which is a measure of the systems profitability on the long term, was lower at LC3 (3.8%), HC3 (10.8%) and HC1 (12.6%), and higher at HC2 (62%) and MC1 (37%). This high variation is expected in small farms, since they usually lack of accurate accounting records and business plans (Valenti et al., 2021). Besides, rural credit and business opportunities offers are hardly achievable by small producers. Consequently, most of the aquaculture farms in Brazil are not economically sustainable (Valenti et al., 2021). Nevertheless, many opportunities exist to overcome this issue. The precise record of financial and production data, the compliance with the regulations for obtaining credit, diversification of markets and products, and equity of opportunities among small and big farms would strengthen the activity (Valenti et al., 2021).

The aquaculture of low-trophic level fish is very important for the subsistence of rural populations worldwide (Ali et al., 2016; Béné et al., 2016;

Zhang et al., 2011). Lambari production started as an alternative income source for the tilapia producers who were outcompeted by the larger investors, and remains a social relevant activity (Valenti et al., 2021). All systems studied rely on local labor and eight farms are over 10 years in the activity, which indicates that lambari aquaculture contributed to the construction of self-identity of the farmers as aquaculture producers, allowing them to maintain their rural livelihoods (Goswami et al., 2017; Silva et al., 2020). Nevertheless, LC farmers contributes larger to the local economy as they purchase their inputs and sell their products locally. This fact indicates that the increase in technification of the activity may increase the economic performance and attract larger investors, but at a cost of contributing less to the local development and excluding smallholder farms which can be an issue for sustainability. For facing that, public policies should focus on diverse solutions for attending the problems of small, medium and large producers, instead of a single-oriented development plan (Brugère et al., 2019; Valenti et al., 2021).

5. Conclusion

The lambari aquaculture has different performances of sustainability, depending on the control of the key variables by the systems operators. Low control farms performed better at the social dimension, contributing mainly for the local socio-economic development and for the maintenance of rural livelihoods. On the other hand, moderate and high control farms performed better at the environmental and economic dimensions, because they use natural resources more efficiently and achieve higher productivity and profitability. Results indicate that the issues of smallholder aquaculture systems are variable among the three dimensions of sustainability, which claims for strategies towards the sustainable development that consider the diversity of problems in a holist perspective. For that, a systemic approach and a multi-criteria assessment, based on the biophysical aspects of the systems, such as the five sector sustainability assessment, can be a useful tool.

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CONCLUSÕES GERAIS

- Os sistemas de produção de lambari dependem majoritariamente de recursos não-renováveis, ou de baixa renovabilidade, independentemente do nível de controle adotado pelo produtor (baixo, moderado ou alto).
- Os principais recursos utilizados são ração comercial e água, sendo que os sistemas de baixo e médio controle dependem principalmente de água subterrânea, que é ambientalmente mais custoso comparado ao uso da água superficial.
- Estratégias de produção que incluem: mudança na fonte de abastecimento hídrico, controle de fertilização, aumento de sobrevivência na produção de alevinos, e substituição da fonte de proteína animal por fontes vegetais na ração, resultam em aumento na performance em emergia e na resiliência dos sistemas.
- Esforços ainda são necessários para melhores práticas de manejo da produção da lambaricultura, mas os resultados encontrados no capítulo 1 destacam que mudanças simples fazem a diferença na sustentabilidade dos sistemas.
- Além da provisão de peixes, os viveiros escavados de aquicultura de água doce fornecem serviços e desserviços ecossistêmicos que dependem das funções ecológicas desse tipo de sistema.
- Os serviços de regulação hídrica e regulação do microclima são características positivas inerentes ao sistema, e dependem das funções ecossistêmicas de recarga das águas subterrâneas e evaporação.
- A absorção e as emissões de gases do efeito estufa variam de acordo com as práticas de manejo aplicadas ao sistema produtivo, e neste estudo, apresentou um efeito neutro no serviço de regulação climática global.
- O efluente de qualidade eutrófica das fazendas estudadas causa o maior desserviço, uma vez que provoca o desvio de recursos para a recuperação da qualidade da água.
- O balanço entre as externalidades positivas e negativas na aquicultura do lambari indicam que os benefícios superam os prejuízos, desde que o sistema opere sob a capacidade de suporte da natureza.

- A lambaricultura tem diferentes desempenhos de sustentabilidade, dependendo do controle de variáveis produtivas pelos operadores dos sistemas.
- As fazendas de baixo controle apresentaram melhor desempenho na dimensão social, contribuindo principalmente para o desenvolvimento socioeconômico local e para a manutenção do modo de vida rural.
- As fazendas de moderado e alto controle apresentaram melhor desempenho nas dimensões ambiental e econômica, pois utilizam os recursos naturais de forma mais eficiente e alcançam maior produtividade e lucratividade.
- Os resultados encontrados no capítulo 3 indicam que os problemas dos pequenos produtores aquícolas são variáveis entre as três dimensões da sustentabilidade, o que demanda uma abordagem sistêmica e uma avaliação multicritério, com base nos aspectos biofísicos dos sistemas.

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